COMPARING TANGIBLE AND MULTI-TOUCH INTERFACES FOR A SPATIAL PROBLEM SOLVING TASK

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Sijie Wang

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APPROVAL

Name: Sijie Wang

Degree: Master of Science

Title of Thesis: Comparing Tangible and Multi-touch Interfaces for a Spatial Problem Solving Task

Examining Committee: Dr. Marek Hatala
Chair

____

Dr. Alissa Antle,
Senior Supervisor,
Assistant Professor,
School of Interactive Arts and Technology

____

Dr. Bernhard Riecke,
Supervisor,
Assistant Professor,
School of Interactive Arts and Technology

____

Dr. Chris Shaw,
External Examiner,
Associate Professor,
School of Interactive Arts and Technology

Date Approved: December 07, 2010

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Abstract

This thesis presents the results of an exploratory study of a tangible and a multi-touch interface. The study investigates the effect of interface style on users' performance, problem solving strategies and preference for a spatial problem solving task. Participants solved a jigsaw puzzle using each interface on a digital tabletop. The effect of interface style was explored through efficiency measures; a comparative analysis of hands-on actions based on a video coding schema for complementary actions; participants' responses to questionnaires; and observational notes. Main findings are that tangible interaction better enabled complementary actions and was more efficient. Its 3D tactile interaction facilitated more effective search, bi-manual handling and visual comparison of puzzle pieces. For spatial problem solving activities where an effective and efficient strategy is not important, a multi-touch approach is sufficient. The thesis uniquely contributes to understanding the hands-on computational design space through its theoretical framing and empirical findings.

Keywords: tangible user interface; multi-touch interface; complementary action; jigsaw puzzle; problem solving strategy; digital tabletop

We have designed so many clumsy machines, so ourselves look less clumsy.

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Glossary

Adjustment action (Ad)	When a participant quickly manipulates one or more jigsaw puzzle pieces or the reference image to move them around in order to further task goals immediately.
Complementary action	Any organizing activity that recruits external elements to reduce cognitive load.
Direct connection (DC)	When a participant mentally determines where a jigsaw puzzle piece will fit and physically manipulates it only to connect it, resulting in a correct connection.
Exploratory action (Ex)	When a participant physically manipulates a jigsaw puzzle piece to explore where it might fit or organizes the puzzle space, but doesn't end up with a correct connection.
Indirect connection (IC)	When a participant physically manipulates a jigsaw puzzle piece in order to determine where it will fit and ends up with a correct connection.
Multi-touch interface	An interface that can simultaneously detect and resolve three or more finger touch points.
Off-task event (OffT)	When a participant switches to non-task related affairs.
On-task-non-touch (ONT)	When a participant stops touching any object on the screen for a certain period but is still attending to the task.
Tangible user interface	An interface that couples digital information to physical objects or environments to augment the real world.

Chapter 1

Introduction

1.1 Overview

Since the concept was first defined by Ishii and Ullmer [34], tangible user interfaces (TUIs) have drawn a lot of interest because of their advantages over traditional mouse and keyboard-based Graphical User Interfaces (GUIs) [20, 33, 74]. TUIs enable an easier way to interact with computers by utilizing the users' existing skills rather than requiring them to learn to use new input devices and understanding abstract outputs on the screen. Interacting with TUIs can be as comfortable as manipulating an everyday physical object.

Recently many novel input technologies have been invented for GUIs. Multi-touch may be one of the most popular among them, given its fast spread on commercial products such as cell phones and tablets. By adopting multi-touch, GUIs on these devices become capable to accept more intuitive, gestural and bimanual input, which were impossible with mouse-based GUIs. The learning curve has been so shortened that even young children can effortlessly enjoy the cutting-edge technology [15].

TUIs and multi-touch interfaces are both frequently praised using the same word - "intuitive". However, a multi-touch interface is still distinct from a TUI. Two of the most significant differences are related to the manipulation space and the feedback modality. The manipulation space on most multi-touch screens is two-dimensional, all input and output are restricted to the screen. TUIs are three-dimensional, in which the third dimension enables not only more interaction space but also richer spatial information. Although lots of effort has been devoted to incorporate tactile feedback on GUI devices [27, 56], meaningful tactile feedback is still absent because what users can really touch is just a flat screen. With the absence of tactile feedback [68], an obvious consequence is a higher reliance on visual feedback that is used for almost everything, from retrieving information to confirming the results of commands. However, this does not mean multi-touch has fewer benefits when compared to TUIs. Practically speaking, TUIs usually need a much longer implementation process than multi-touch interfaces. They are also less portable, which makes multi-touch superior in this regard, as summarized in Table 1.1. A more comprehensive comparison will be given in Section 2.6.

Table 1.1: The main differences between TUI and multi-touch.

	TUI	**Multi-touch**
Tactile feedback	Yes	No
Manipulation space	3D	2D
Implementation	Complicated, expensive	Easy, cheap

TUIs and multi-touch interfaces are not mutually exclusive. A hybrid of them is becoming more and more common, especially on interactive tabletops like Microsoft Surface and reacTable [38, 42]. These devices have the ability to recognize both finger touches and physical objects. For example, Microsoft Surface allows users to put a cell phone on the tabletop, which serves as a tangible agent in the subsequent interaction, and expands a graphical menu around the cell phone on the multi-touch screen for related tasks such as browsing photos in the phone memory.

In a task as simple as casual photo browsing, a multi-touch interface seems to be the obvious choice as the display can be dynamically changed, speed and accuracy are not much of a concern, and the need for mental thinking is little. But when faced with a more complicated situation, for example, a spatial problem solving task that requires a significant amount of hand-brain collaboration, knowing how to choose one from the other or how to combine the two interfaces is more challenging.

To address this problem, designers need to understand how the differences between these two interface styles may affect users' performance and experience. In terms of performance, several comparative studies have been done. For example, the presence of tactile feedback on TUI's allows a faster acquisition of a tangible control widget than a graphical widget [27, 56]. A tangible keyboard supports faster typing than a virtual one because of its tactile feedback [58, 63]. However, these studies focus more on motor behavior aspects and simple selection or control tasks. Little has been done to investigate how well the interfaces support users' cognitive activities during more sophisticated problem solving tasks. In a study which is similar to this study, the authors found that the ease of manipulating a tangible object allowed more physical actions to occur during a problem solving task, which may have helped users develop a mental model to solve the problem [4]. However, whether an "intuitive" multi-touch interface can have this similar advantage or not still needs to be investigated. This answer is important when designing an interface for a task that requires a lot of mental effort (e.g. spatial problem solving tasks such as urban planning).

1.2 Research Goal

In order to explore how tangible and multi-touch interfaces affect users' performance, problem solving strategy and preferences, a comparative user study was designed to collect quantitative and qualitative data from a jigsaw puzzle solving task. By doing this, the advantages and disadvantages of these two novel interfaces can be better understood. The knowledge can be used to help designers make better decisions when they need to choose one for a specific task or when designing a hybrid tangible and multi-touch interface.

1.3 Thesis Guide

Below is a brief overview of the structure of this thesis.

In Chapter 2, a literature review is given. First is the introduction and historical review of tangible user interfaces, multi-touch interfaces, and interactive digital tabletops. Second, tangible user interfaces and multi-touch interfaces are analyzed in more detail based on their characteristics. Third, existing empirical studies of the two interfaces and related theoretical frameworks are reviewed. Fourth, a previous study that sets the foundation of this study is summarized. At the end of this chapter, the research question of this study is outlined.

In Chapter 3, the technical details of the research instrument are provided. The details show how the digital interactive tabletop was designed and implemented to meet the study requirements, in both the hardware and software aspects.

In Chapter 4, the details of the study design are outlined, including the goal of the study, the task, the research instruments, the participants, the measurements and the data analysis method.

In Chapter 5, results of the user study is presented in three main sections: performance, problem solving strategy and subjective preference. In addition, demographic variables are analyzed to investigate their effects on the three main measurements.

In Chapter 6, interpretations of the study findings are provided in the context of the research questions. Based on the results, design implications are made for the design of tangible and multi-touch interfaces. The findings of this study are also compared to related studies.

In Chapter 7, the outcomes and contributions of this study are summarized. The known limitations of the study are given, as well as the suggestions for future research.

In the Appendices section, the pre- and post-questionnaires and the session scripts that were used in the study are provided.

Chapter 2

Background

2.1 Overview

In this chapter, a review of the relevant literature is presented. The review covers the most important concepts that will be used in this study, including the concepts and history of the major interface styles: tangible user interfaces and multi-touch interfaces. It also covers one the most popular devices that incorporate these two types of interfaces: digital tabletops, which is also the device used in this study.

In order to discuss the characteristics of these interfaces and devices through a theoretical lens, existing theories on direct input, bimanual actions, the space- vs. time-multiplexed interfaces, affordances of specialized input devices and complementary actions are reviewed. The findings of relevant empirical studies of tangible and multi-touch interfaces are summarized. Two related interface frameworks are introduced to situate this study in the realm of human-computer interaction. A previous work that directly sets the foundation of this study is also introduced.

At the end of this section, the research questions are proposed.

2.2 Tangible User Interfaces

In 1995, Fitzmaurice, Ishii and Buxton described a new paradigm called "graspable user interface", which is a blend of digital and physical user interface elements [20]. Based on this work, Ishii and Ullmer proposed the term "tangible user interface" to describe new kinds of physical interfaces in the digital world [34]. Their vision was that tangible user interfaces couple digital information to everyday physical objects and environments in order to augment the real world. A widely-known non-digital example is the calculating device abacus, which is neither an input device nor an output device but an integration of both. Its components, including the beads, rods and the frame serve as both *physical representations* and *physical controls* for the numerical values and operations. Historically, tangible user interfaces were also called as "Manipulative User Interfaces" [28] and "Embodied User Interfaces" [17].

One may argue that traditional input devices such as keyboards and mice are also tangible in form. A more comprehensive outline that distinguishes tangible user interfaces (TUIs) from traditional input devices was proposed by Fitzmaurice et al. [20], and Ullmer and Ishii [71] and includes the following unique characteristics of TUIs:

- TUIs can integrate input and output, so users can directly interact with objects in the same input-output space. In contrast, mice and keyboards only serve as an input device for indirectly interacting with the graphical information displayed on output devices;

- TUIs can display output information, and these physical representations can be coupled to underlying digital models, the mechanisms of interactive control, and/or digital representations [71];

- TUIs encourage asymmetric two-handed interactions [23, 39]. Asymmetric two-handed interactions refer to those bimanual interactions in which each hand plays a different role as explained in Guiard's Kinematic Chain theory [23]. More details on asymmetric bimanual interaction will be discussed in Section 2.5.2;

- TUIs can be specialized to the context at the cost of general-purpose flexibility, which means each tangible widget is specialized for a certain type of input and representation, offering more opportunities for interactions and information representations in both of them;

- Because specialized tangible widgets are provided for each task, users can perform multiple tasks in parallel instead of being constrained by a single input device. That is, TUIs are space-multiplexed rather than time-multiplexed. The advantages of space-multiplexed over time-multiplexed will be explained in Section 2.5.3;

- Users can use a wider range of full hand skills to directly manipulate the tangible objects, instead of using simple and generic agent devices;

- Because they are spatially distributed, TUIs are intrinsically suited to collocated co-operative work as opposed to traditional Graphical User Interfaces (GUIs) with which users have to share one mouse and keyboard;

- The sharing of TUIs also leverages the power of distributed cognition which refers to using physical objects and the environment to support memory, learning and inter-personal communications [31].

How these characteristics are beneficial will be further discussed in Section 2.5.

2.3 Multi-touch Interface

Multi-touch refers to a touch system's ability to simultaneously detect and resolve three or more finger touch points [1]. The Input Research Group at the University of Toronto developed the first multi-touch system in 1982. But arguably it was not well-known until the announcement of Apple's iPhone in 2007. Technologically, multi-touch can be implemented in several ways. The most popular ways are the capacitive and resistive approaches that are widely used on handheld devices, and the computer-vision based approach that is used on large interactive surfaces such as tabletops and walls [25].

A multi-touch interface has some similar characteristics to a TUI.

- A touchscreen also integrates input and output spaces. Users interact with the on-screen objects directly with their fingers, without using another agent;

- Multi-touch interfaces support two-handed interactions and performing tasks in parallel. However, it has been suggested that users tend to use a single hand in some circumstances [68]. This issue will be discussed later in Section 2.5.2;

- The space-multiplexed nature also makes multi-touch interfaces suitable for collocated cooperative work, especially in the form of large multi-touch surfaces.

2.4 Interactive Digital Tabletops

As perhaps the most common component in home and office environments, tables can be found almost anywhere. People can either individually or collaboratively change the content being displayed on the table by adding or removing photos, printed materials and physical objects on the table.

By adapting new technologies, traditional tables can be transformed into highly interactive multi-user devices, whose content can be dynamically changed by the computer. This turns the tabletop into an innovative interface for interacting with the digital world in a more natural way (e.g. by directly touching the content or manipulating physical objects on the surface).

Compared to other devices, interactive tabletops are more closely related to TUIs and multi-touch for the following reasons:

- Direct touch. Unlike indirect multi-touch pointing devices, (e.g. a built-in multi-touch touchpad on some laptop computers), the surface of the tabletop serves as both output and input so that users directly touch the object they want to interact with, without using another pointing device. This is the natural way we interact with most physical objects in our daily life;

- Large and horizontal. Similar to non-computational tables, interactive tabletops are mostly designed as horizontal surfaces and are larger than many other display devices such as computer monitors. A tabletop can be easily used as a bearer for physical objects. Virtual items can also be made into a size large enough for comfortable finger touches. A large horizontal surface with no specific orientation may also encourage collocated collaborative work between multiple users;

- A hybrid of multi-touch and tangible. Since many interactive tabletops take the computer-vision approach for implementation purposes, in addition to finger touches, they can also detect physical objects that are placed on the surface. These objects can therefore be used as tangible widgets for interacting with the digital information. For example, VoodooSketch is a system designed to incorporate physical interface palettes to multi-touch surfaces on which shortcuts of application functionalities can be customized by users [9].

Tabletops have been intensively used to explore new gaming experiences [3, 11, 49, 50] and new ways of data manipulation [20, 22, 65, 67, 70, 72].

2.5 Related Work

TUIs and multi-touch interfaces are both praised for their "naturalness". However, the meaning of the term "natural" is hard to define. Their virtues should be analyzed from a more theoretical perspective. Existing literature provides several theories as well as a framework that may be helpful in taking a deeper look at their advantages over traditional input and output devices. These concepts and frameworks will be introduced in this section.

Section 2.5.1 to Section 2.5.4 explain why tangible and multi-touch interfaces may achieve a higher efficiency than traditional interfaces as a direct, bimanual and space-multiplexed interface. Section 2.5.5 analyzes tangible interfaces using the complementary action theory to show their advantages in offloading mental activities onto physical actions.

2.5.1 Direct Input

Numerous research projects have focused on direct-touch input on tabletops [16, 52, 53, 61, 62, 77]. Direct-touch is considered to be preferable to indirect input because it's more similar to the way we interact with everyday objects.

However, whether direct touch can result in a better performance or not is related to the interface style and the task. Forlines et al. claimed that direct multi-touch is superior to indirect mouse input for bimanual input tasks, but when the task requires only a single-point, an indirect single mouse input may be more appropriate [21]. As a confirmation and extension, the study conducted by Schmidt et al. focused specifically on multi-touch interfaces, showing that direct multi-touch input can achieve a higher efficiency than indirect multi-touch in a bimanual image matching task [60].

2.5.2 Bimanual Actions

People interact with the physical world using a diverse range of two-handed actions. But most computers can only support a single-handed input, or very simple two-handed actions such as typing on the keyboard with two hands. Lots of studies have been done to explore possible alternative solutions that can support bimanual human-computer interaction [10, 29, 30, 46, 51].

In an early study, Kabbash et al. found two empirical benefits when using two hands rather than one to perform a task [39]. First, dividing the labor across two hands allows each hand to stay in a relatively stable position thus avoiding frequent movements. For example, when performing a drawing task, one hand can remain close to the toolbox to select the tool while the other hand stays on the canvas to do the drawing. Second, two hands can carry out subtasks simultaneously to reduce the overall completion time.

Furthermore, Leganchuk et al. chose an area sweeping task to investigate the benefits of two-handed input, using two perspectives: manual and cognitive [48]. The result of their study showed that the manual benefits of bimanual input come from the higher degrees of freedom available to the user, which increases the time-motion efficiency. Bimanual input also allows the user to physically perform subtasks in parallel which reduces the cognitive load, instead of planning or visualizing them in a sequential manner. Apart from these two studies, many others also provided valuable insights [7, 47, 60].

Two-handed actions are not always better than one-handed. Subtasks should be designed in a similar way as to how we do them in the physical world. Guiard characterized our daily two-handed behaviors with the kinematic chain theory [23]: the non-dominant hand sets the kinesthetic reference frame first, then the dominant hand performs actions within this frame. The non-dominant hand's action is coarser than the dominant hand. A typical scenario is when writing on a piece of paper. Writers usually use the non-dominant hand to roughly grip the paper in a comfortable position, then use the dominant hand to write on it, which requires more precise actions. Studies that followed indicate that designing two-handed interactions according to Guiard's model can reduce cognitive load and achieve a faster completion time than a single-handed design [8, 39]. In contrast, assigning two independent subtasks to each hand results in even worse performance than using one hand [39], similar to the situation when "tapping the head while rubbing the stomach" is challenging to coordinate.

2.5.3 Space-multiplexed and Time-multiplexed

Fitzmaurice proposed that input devices could be classified as either *space-multiplexed* or *time-multiplexed* [18, 19]. A space-multiplexed input has a dedicated transducer associated with each of its functions. These transducers are physically independent and can be accessed simultaneously by the user. In contrast, a time-multiplexed input uses a single device to access multiple functions, so the operations must occur at different points in time.

Fitzmaurice's study also provides evidences that a space-multiplexed input is superior to a time-multiplexed input configuration. In his shape matching task [18], space-multiplexed configurations allowed a faster completion time mainly because of permitting parallel activities. Even when the parallel activities are factored out, this advantage still exists because acquiring physical devices is faster than acquiring virtual controllers. Also when using a time-multiplexed configuration, users must plan ahead when switching among tools and modes to achieve their goals. A space-multiplexed configuration minimizes interaction modes and keeps the interaction continuous, so users can focus on higher level thinking, such as the strategy behind the actions rather than on the complex set of subtasks.

2.5.4 Affordances of Specialized Input Device

Fitzmaurice defined a specialized device as one having a physical shape and manipulation characteristics that roughly match the virtual logical controller [18]. Otherwise it is considered to be a generic device, like a mouse. His results found that a "strong-specific" design applied to input devices resulted in better performance than the "weak-generic" design.

Couture et al. conducted another study comparing generic and specialized tools in a geographical task [14]. The result showed that the physical constraints of a specialized device helped users maintain the relationships between both the physical and virtual objects. This is also part of the reason why a specialized device can outperform a generic one.

2.5.5 Complementary Actions

Kirsh defined a complementary strategy as any organizing activity which recruits external elements to reduce cognitive load [43]. A complementary strategy is a way for an individual or a group to adapt to the environment in order to improve their cognitive strategies for problem solving. The actions involved can be pragmatic or epistemic.

Epistemic actions are those used to change the world to simplify the task but don't necessarily bring the subject directly closer to their goal. Epistemic actions can do this in three ways [44]:

1. Reduce space complexity: reduce the memory load in mental computation.

2. Reduce time complexity: reduce the number of steps needed in mental computation.

3. Reduce unreliability: reduce the probability of error in mental computation.

An example of epistemic action is when playing Tetris, players manipulate a piece to better understand how it looks after rotation. Such an action does not directly lead to the solving of the puzzle but does make the subsequent play easier by offloading the mental rotation to a physical rotation.

In contrast, pragmatic actions are those used to bring the individual closer to the goal (e.g. solving the puzzle, winning the Tetris game).

Although supporting complementary actions is not confined to TUIs, it's evident that for some tasks TUIs are more effective than traditional mouse-based interfaces. The reason could be the physical manipulation TUIs afford. Direct manipulations on physical computational objects can make abstract concepts more accessible [57]. Antle et al. compared the differences between using a TUI and a mouse-based GUI for children to solve jigsaw puzzles [4]. They found that children using a mouse tend to use a less efficient trial and error approach to solving the puzzle. When solving the tangible version jigsaw puzzle, participants used more hands-on exploratory actions, many of which were epistemic. As the solving process moved along, there was a significantly larger chance in the TUI group that children picked up a piece and put it directly to the correct position without hesitation. This could indicate that they gained a more clear mental model of the puzzle through physically interacting with the puzzle. This mental model made the solving easier as it went on, as opposed to the mouse group for which the puzzle never got easier.

Several other tangible user interfaces were also developed with the underlying assumption that tangible interaction can make the spatial task easier to solve [33, 70, 74]. But multi-touch interfaces have not been explicitly studied with respect to this kind of motor-cognitive advantage.

In conclusion, how well a multi-touch interface can support complementary actions needs to be further investigated. To address this problem, using a tangible user interface to compare with a multi-touch interface is a valid option since similar work has been done with tangible interfaces, and it's evident that tangible interfaces can effectively support complementary actions. Although such a comparison focuses more on the cognitive aspect, the efficiency of the interfaces should be taken into account as well. Based on the literature review in Section 2.5.1 to Section 2.5.4, a direct multi-touch interface that supports bimanual interaction is expected to be more efficient than the other multi-touch interface types. The tangible user interface to be used in the comparison should also be a specialized input device to achieve a better performance. In Section 2.6, some related empirical studies will be reviewed to further clarify the design of such a comparative study.

2.6 Empirical Studies of Tangible and Multi-touch Interfaces

In previous studies, mice served as a good benchmark representing the most common input device on GUIs (Graphical User Interfaces). But the focus of research has been shifting to novel technologies such as TUIs and multi-touch. There are several similarities between TUIs and multi-touch, as listed in Table 2.1.

Table 2.1: Differences and similarities between TUI and multi-touch

	TUI	**Multi-touch**
Tactile Feedback	Yes	No
Manipulation space	3D	2D
Specialized device	Yes	N/A
Space-multiplexed	Yes	Yes
Support two-handed action	Yes	Yes

Being a space-multiplex device that supports bimanual interactions, the question that arises is: can multi-touch have the same advantages as TUIs? Because it does not have a physical form, it cannot be categorized as a specialized or non-specialized device. Another question pertains to how well multi-touch interfaces can support complementary actions: Is the direct touch on the screen similar to the physical manipulations on TUIs in terms of enabling motor-cognitive activity?

Although both promise a natural interaction experience, there are two major differences between multi-touch and TUI:

- Users can not lift or hold a piece with their hands when using a multi-touch interface, so the manipulation space is 2D instead of 3D;
- There is no tactile feedback on a multi-touch interface, so it relies more on other types of feedback than a TUI does, such as visual feedback.

The effect of such differences has yet to be fully investigated but there are some initial studies in literature.

Terrenghi et al. compared a physical and a multi-touch interface for a puzzle task and a photo sorting task [68]. Their results show a fundamental difference between these two UI-styles. Some of the findings are particularly of interest.

- They found that although they deliberately designed the digital multi-touch tabletop interaction to facilitate bimanual interaction, most participants actually used one-handed interaction on the multi-touch surface;

- In the physical mode, two hands worked together in diverse ways, especially asymmetrically, such as the non-dominant hand providing a frame of reference for the dominant hand's actions when selecting or placing. These behaviors were much rarer in the digital condition;

- Participants used a diverse range of strategies with the physical photo or puzzle pieces during the task, such as organizing them spatially into several groups (i.e. epistemic complementary actions) in order to solve the problem.

Their study reveals a significant difference between unimanual and bimanual actions on multi-touch versus physical interfaces. But the results do not show how these two interface styles affect user's cognitive activities. Although the physical interface is arguably in the same form as a tangible interface, digital feedback is missing since no computing technology was involved in the physical condition, reducing the comparability between the physical condition and the multi-touch condition.

Kirk et al. conducted case studies of two hybrid interactive tabletop systems: *VPlay* and *Family Archive* [42]. Their work contributed several valuable guidelines for designing mixed tangible and multi-touch interfaces. They specifically investigated two aspects.

- How to choose the form of interface elements to provide key features of a system, being digital or physical?

- How the digital domain should emulate the physical world?

They suggested that physical objects are particularly suitable in environments where eyes-free control and rich or accurate control are needed. Interacting with a 3D world on a 2D surface like a multi-touch screen is also challenging to design. As a case study, their work sets the first step for future research in exploring tangible and multi-touch interfaces.

Hancock et al. conducted a study comparing a multi-touch interface and a tangible controller for a 3D object manipulation task and a data exploration task [26]. The tangible controller they used was a customized mouse with a trackball mounted on top. As opposed to Terrenghi et al., they focused more on quantitative performance data, such as completion time and accuracy. In their experiment, the tangible control device provided superior indirect control with higher precision, while the touch interface provided a more direct connection between the user and the information being touched. But little was done regarding whether such directness makes the task easier or not. Also, the tangible widget they used was not strictly a tangible user interface since it only served as an input device but not a representation.

Tuddenham et al. compared users' performance on a tangible user interface, a multi-touch interface, and a mouse-and-puck interface for a shape matching task [69]. Quantitatively, the results demonstrated that the tangible items were easier and more accurate to manipulate and faster to acquire than the other two interfaces. Qualitative analysis also showed the problem of exit error on multi-touch interfaces, which was caused by the slight shift of a contact point such as lifting a finger off the screen. For this reason, the multi-touch interfaces were shown to be less effective for fine-grained controls than TUIs.

In addition to these research projects, there have been many excellent designs demonstrating the benefits of TUIs.

Marble answering machine uses physical marbles to represent messages received by the machine [64]. Dropping a marble on a dish plays the corresponding message. Thus the user can easily determine the number of new messages by looking at the number of marbles, and control playback with actions as simple as dropping the marbles.

Augmented Urban Planning Workbench allows users to manipulate physical building models on a tabletop surface to see their effect on air flow, shadows and reflections, which are calculated and presented digitally in realtime [33].

ReacTable uses physical objects on a tabletop as the representation of different music generators and controllers [38]. By organizing them in space and manipulating their position, users can generate sound and music.

There are other research projects that aim to exploit the advantages of TUIs for input tasks [66], data visualization and manipulation [22, 24, 28, 37, 70, 75], musical applications [13, 54], 3D modeling [2], and Geoscience applications [14, 55].

However, given the fact that multi-touch interfaces are much easier to implement than

TUIs, it is worth further investigating the impact of their differences to help designers make the best choice among interface styles, as well as how to integrate both tangibles and touch for a particular task or a particular device (e.g. an interactive tabletop).

2.7 Frameworks

Several frameworks for designing or analyzing TUIs have been proposed. These frameworks can be used to relate the research of TUIs to the broader picture of HCI research, as well as to inspire new designs for various contexts.

2.7.1 Reality-Based Interaction Framework

The Reality-Based Interaction (RBI) framework proposed by Jacob et al. focuses on the design of post-WIMP interfaces [36]. Interacting with post-WIMP interfaces is considered to be similar to our interaction with the non-digital world. RBI is thus intended to be used to analyze the similarity between a post-WIMP interface and the physical world from the perspective of four themes:

1. Naïve Physics, such as gravity, friction, velocity, and the persistence of objects.

2. Body Awareness and Skills, which are the awareness of the position, the range of motion, and the sense of one's body parts.

3. Environment Awareness and Skills, which are using the clues embedded in the environment to facilitate the sense of orientation and spatial understanding.

4. Social Awareness and Skills, which are the sense of the presence of others and the interpersonal communication.

Our study focuses on the first two themes. Therefore, to make sure the multi-touch interface used in the comparison is comparative to its tangible counterpart, it should be designed with the consideration of emulating naïve physics and leveraging the power of body awareness and skills.

2.7.2 Degree of Coherence

Koleva et al. proposed a framework based on the idea of *degree of coherence* between physical and digital objects [45]. Corresponding with each level of coherence from weak to strong, TUIs can be categorized as:

1. *General purpose tools* are those that can be used to manipulate any one of the digital objects, such as mice and joysticks.

2. *Specialized tools* are those that can interact with many digital objects but have a more specialized function. For example, various types of physical optical instruments from the Illuminating Light system [73] and the physical drawing tools from the Surface Drawing system [59].

3. *Identifiers* are those that are used as representations for computational artifacts. For example, the bar-coded objects in the WebSticker system [32].

4. *Proxies* are those that have a closer bond with digital counterparts than identifiers, and can be used to manipulate digital objects. For example, the physical architecture models in metaDesk [70].

5. *Projections* refer to the relationships that physical objects project, such as their properties, onto digital representations. For example, the physical human activities that are represented by digital patterns on the wall in the ambientRoom [35].

6. *Illusions of same objects* are those when the physical and the digital forms are coupled as one.

The direct multi-touch interface to be used in this study does not involve any sort of "tool", the input and output spaces are tightly integrated so that the tangible interface should ideally be designed in the same way which is on the level of *Illusions of same objects*.

2.8 Building On Previous Work

Closely related to this study, Antle et al. developed a categorization scheme for analyzing user behaviors during a jigsaw puzzle task [4, 5]. They proposed three categories of actions: *direct placement actions, indirect placement actions* and *exploratory actions*. Direct placement is when the user picks up a piece and places it to the correct position without hesitation, which means he or she has already determined where it should fit through mental operations. The action does not simplify the task but makes actual progress of the task, so it is *pragmatic* and *non-complementary*. Indirect placement is when the user picks up the piece, and places it to the correct position after manipulating it (e.g. rotating, translating or comparing to the others). Such action indicates that the user did not yet know the correct position for the piece, and is using hand actions instead of imagination to find the answer, which indicates offloading a portion of mental activity onto the actions of the hand. Thus it is a *complementary action*. Because it ends up with a correct connection, it is also *pragmatic*. An exploratory action is the kind of action that does not necessarily bring the user closer to the goal (finishing the puzzle), but makes subsequent solving easier. So it is *epistemic* and *complementary*. A prototypical example is sorting pieces into piles of edge pieces, corner pieces and so on. This categorization scheme is useful for analyzing user's problem solving strategies and temporal patterns of actions. Table 2.2 summarizes these three action classes.

Table 2.2: The three action classes categorized by complementary or non-complementary, and pragmatic or epistemic.

	Complementary	**Non-complementary**
Pragmatic	Indirect placement	Direct placement
Epistemic	Exploratory action	N/A

In the study by Antle et al., physical, tangible and mouse-based jigsaw puzzles were compared. They analyzed the result of the performance and the puzzle solving strategy. For performance, they found that participants completed the physical and the tangible puzzles faster and more successfully than the mouse-based puzzle. For the strategy, participants spent more time making direct placements and exploratory actions with the tangible interface than the mouse-based interface. The temporal analysis also showed a pattern of exploratory actions followed by direct placements. This could possibly indicate that participants built the mental model by performing exploratory actions. The mental model later allowed them to mentally determine the correct position of the puzzle pieces. So when using the tangible puzzle, the task actually got easier as the solving progressed, while the mouse-based interface only supported a low efficient trial-and-error approach and the difficulty of the task did not decrease. They also proposed that players would offload more mental activities to hand actions (i.e. more indirect placements) with the tangible interface, but this was not supported by the data.

Their methodology is adopted in this study, but with a different comparison (tangible vs. multi-touch interface, rather than physical vs. tangible vs. mouse-based interface), and a different subject group (adults rather than children).

2.9 Research Question

The research question of this study is:

How do tangible user interfaces and multi-touch interfaces affect the users' experience of a spatial problem solving task?

It consists of three more detailed questions:

- *RQ1: How does interface style affect users' performance when solving a jigsaw puzzle?*
- *RQ2: How does interface style affect a users' puzzle solving strategy?*
- *RQ3: How does interface style affect a users' subjective preference?*

Because such comparison has not yet been done in previous work, there is not enough literature support for any prediction, and there are too many factors that vary between the two interfaces to design a comparative experiment, this study is more exploratory. However, the result can still be used to confirm or controvert the findings of previous related studies.

By conducting this exploratory study, new design guidelines can be generated to guide designers when choosing the appropriate interface style, either tangible or multi-touch, or an integration of both, for a spatial task that requires a significant amount of problem solving.

Chapter 3

System Design

3.1 Design Goals

Digital tabletops are particularly suitable for this study because traditionally jigsaw puzzles are played on horizontal surfaces. Digital tabletops can afford both tangible and multi-touch interfaces on the same surface too. To avoid interfering with the measurements on the user experience, the tabletop used in this experiment should be ergonomically comfortable to use, and be able to stably track finger touches and physical objects.

More specific, a stable tracking consists of two parts.

- Location-accuracy. Many existing computer-vision based interactive surface solutions rely on a single-camera and wide-angle lens setup, which causes a low tracking performance in the corners of the multi-touch table. The tabletop used in this study should be able to consistently detect a finger touch or identify an object across the surface, regardless if it happens at the center or the corners;

- Speed. The tabletop should be able to detect a finger or object event with little delay to provide real-time feedback to the user. This requires the cameras running in a high frame rate, the tracking software and the applications being reasonably efficient, and the computational power being competent to perform both tasks simultaneously during the experiment.

A new tabletop was designed and built with these goals in mind. By using a multi-camera setup, the vision system could cover the whole tabletop surface with satisfactory

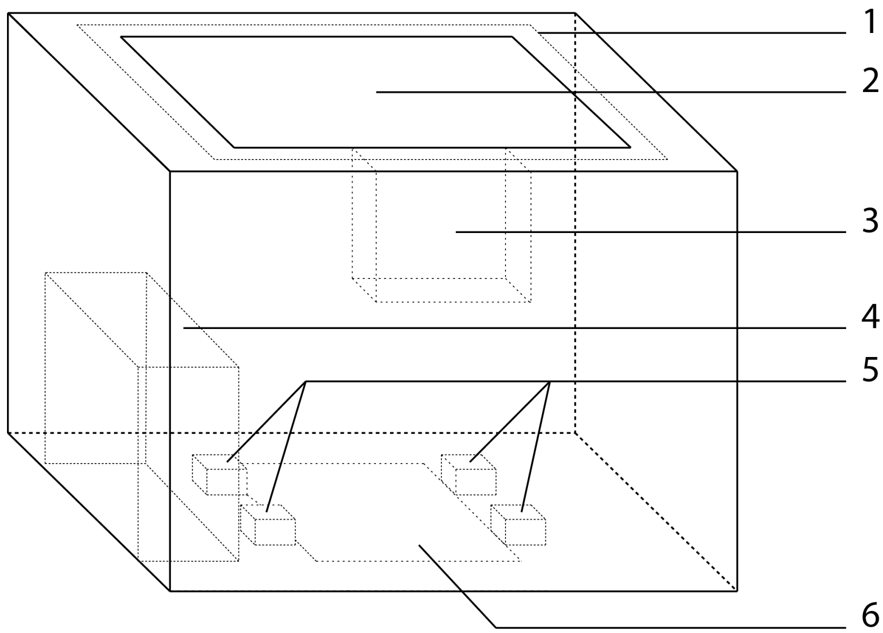

Figure 3.1: Hardware setup of the table: 1. IR LED strip; 2. EndLighten acrylic board and diffuser; 3. Projector; 4. PC; 5. Cameras; 6. Mirror.

image quality for the image processing module, for the purpose of identifying finger touches and fiducial markers.

3.2 System Architecture

3.2.1 Hardware

Figure 3.1 shows the hardware structure of the table. For the computer vision part, the infrared LED (Light-emitting diode) strip wraps around the acrylic board, thus emitting infrared light horizontally into the board. The EndLighten acrylic board scatters the light evenly above the surface to illuminate fingers and objects. The infrared image is then captured by the four Sony PlayStation®Eye cameras and analyzed by the tracking software. For the display part, the image is projected downwards and reflected by the mirror to increase the projection distance so that 89×69 cm screen is covered. The projector has a resolution of 1024×768, thus the screen has an approximate density of 30 DPI. In practice, the PC installed inside the table is dedicated to run the computer vision software. The jigsaw puzzle application runs on the other machine which is connected to the PC by LAN

(Local Area Network).

3.2.2 Software

The finger and object tracking software runs in a Ubuntu Linux system. It is developed by using my dual-camera tracking software StitchRV to support four cameras simultaneously [76]. It consists of five parts:

1. Camera driver. Based on the open source driver library V4L2, a customized video camera driver is written for the purpose of grabbing new frames from each camera in a frame rate of 30 fps and the resolution of 640×480 pixels.

2. Image stitcher. The image stitcher transforms the four images to compensate for the lens distortion as well as removes overlapping parts among them, then stitches them into a complete 1280×960 black and white image for analysis.

3. Finger and fiducial marker finder. This part is done using the reacTIVision tracking library [40, 41]. It analyzes the black and white image and returns a list of finger/fiducial marker information, including the size, angle, position and ID.

4. Communication. All the information returned by the reacTIVision tracking library is sent with TUIO protocol via LAN to the other machine that runs the experiment software.

5. Interface. An interface written in C++ with Qt library provides various of controls of the tracking system.

This tabletop serves as the research instrument, on top of which the tangible and multi-touch jigsaw puzzles were built.

Chapter 4

Study Design

4.1 Research Goal

The goal of this study is to explore how the interface style affects participant's behaviors and strategies when solving a jigsaw puzzle.

The tangible user interface and multi-touch interface are the two interface styles being studied. Their differences can be summarized in these three aspects:

1. Manipulation space. The tangible puzzle has a 3D manipulation space which allows participants to grab a piece in hand and lift it from the surface. The multi-touch puzzle's manipulation space is limited to 2D. All the manipulations have to be done on the flat screen surface.

2. Tactile feedback. For the tangible version of the jigsaw puzzle, all the pieces have a certain weight and shape. This factor creates several possibilities for the participant, such as sensing the quantity of a pile of pieces without eye-gazing. Tactile feedback is absent in the multi-touch puzzle.

3. Digital feedback. For the multi-touch jigsaw puzzle, more forms of digital feedback are possible than in the tangible version because the whole interface can be controlled computationally by the system. An example is when two pieces are brought close enough and there is a correct connection between them, the system can snap them together to complete the connection. More importantly, the snapping effect provides a feedback of the correct connection and prevents incorrect ones from happening.

Correspondingly, these differences might cause different levels of performance and strategies to be developed by participants.

4.2 Task

The user study used a tangible and a multi-touch version jigsaw puzzle as the task. There are several reasons for choosing a jigsaw puzzle solving task according to the literature review [4, 5]:

1. A jigsaw puzzle can leverage the advantages of tangible and multi-touch interfaces, as discussed in Section 2.5. The puzzle solving task can be divided into subtasks that are suitable for bimanual actions, which are supported by the space-multiplexing nature of tangible and multi-touch interfaces.

2. A jigsaw puzzle is a prototypical problem solving task that involves complementary actions [4, 12]. That means it requires a tight coupling of both internal mental operations and physical operations on objects so that it can be successfully solved.

3. The jigsaw puzzle is familiar to the participants, and both the concept and the rules are simple enough to get their hands on it quickly.

4.3 Research Instrument: Puzzles

Because the two interfaces that were used in this study may have been novel for participants, a training session was included. To minimize the order effect, there should be two different puzzles for the two conditions. So, a total of three puzzles were required in the study.

The three jigsaw puzzles each had a different imaginary cartoon theme. The first one was an illustration of a dragon attacking a tower, the second was a pirate ship, and the third was witches, knights and a princess in a castle, as shown in Figure 4.1. Among them, the first puzzle was used in the participant training session, while the other two were used during the formal tasks. Each puzzle was implemented with both a tangible and a multi-touch version on the fore-mentioned tabletop device. Each puzzle had 54 pieces in total, taking 15-45 minutes on average to finish for an adult player. The complete puzzle has a dimension of 35×35 cm.

Figure 4.1: The three jigsaw puzzles used in the experiment.

The two interfaces were designed and implemented to ensure they were comparable, and that the interface style could be isolated from other factors. The two versions of the puzzle were used on the same tabletop surface. The tangible and the graphical pieces were made the same size. The auditory feedback was also identical, although some particular aspects had to be in different forms, such as the visual feedback of connection events, which will be described below.

4.4 The Tangible Interface Condition (TUI)

Figure 4.2 shows an overview of the TUI puzzle. The tangible puzzle was similar to a regular jigsaw puzzle except that each piece had one half of a reacTIVsion fiducial marker on each edge (see Figure 4.4), thus when two pieces were assembled properly, a complete fiducial marker would be made (Figure 4.5) and sensed by the digital table (as described in [6]). By detecting the position and angle of the marker, the application displayed a white circle beneath the connection indicating the connection was correct (Figure 4.6). This circle was presented to provide visual feedback for the TUI puzzle. A "bing" sound was played as the auditory feedback. If the connection was incorrect, the complete marker could not be made so neither visual nor auditory feedback would be given. This design tightly integrated the physical puzzle piece and its digital part which was the white circle, so they acted on the level of *Projections* as discussed in Section 2.7.2. The tangible pieces were also specialized devices, each had a specialized shape can pattern, as discussed in Section 2.5.4.

A reference image showing the complete puzzle was provided on the screen because it was common to have a reference image in a jigsaw puzzle game, and also to make the result of this study comparable to the previous one conducted by Antle et al [4, 5]. For the reference

Figure 4.2: Overview of the TUI puzzle.

Figure 4.3: Overview of the TOUCH puzzle.

Figure 4.4: Two separate markers, each has one half of a fiducial marker on each edge.

Figure 4.5: One fiducial marker becomes complete after a correct connection.

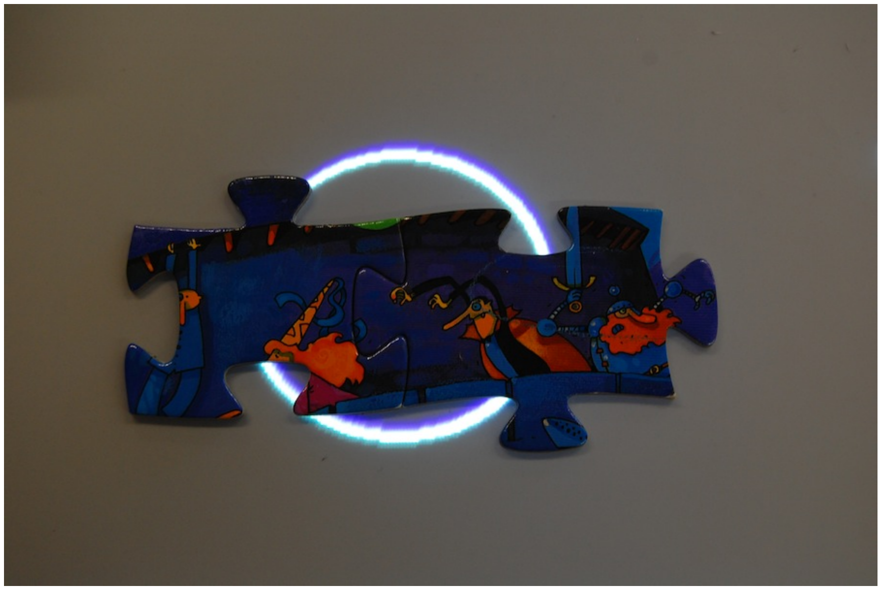

Figure 4.6: A white circle shows up beneath the pieces indicating the connection is correct.

Figure 4.7: The physical block used to control the reference image in TUI.

image, two options were available for the TUI, either by displaying the image virtually on the tabletop screen or by providing a printed image. The former was chosen to make sure the reference image take up the same screen space during both conditions, so it would not cause any difference to the result, such as the puzzle solving strategy.

A physical block was provided to control the reference image. The block had a fiducial marker attached to the bottom, whose position was associated with the position of the reference image on the screen. By manipulating the block, participants could move or rotate the reference image to a position they preferred (see Figure 4.7). To prevent participants from building the puzzle on top of the reference image, which might change the task type from a spatial task to a visual search task, scaling the image or the puzzle pieces was disabled and the size was locked to 80% of the actual size (i.e. the size of the finished puzzle).

4.5 The Multi-touch Interface Condition (TOUCH)

Figure 4.3 shows an overview of the TOUCH puzzle. The multi-touch puzzle recognized common finger gestures used on current multi-touch interfaces, such as using one finger to drag an object, or two-finger panning to rotate it. Such gestures have been widely used in commercial products such as portable touch-screen devices, and numerous research projects [21, 60, 68, 69]. In addition, sweeping actions were assumed to be necessary for the TOUCH puzzle. However during the design study conducted with two participants using physical jigsaw puzzles, such actions were not observed, so this function was not implemented in the final design. The scaling function of the reference image and the pieces was also disabled for the same reason as in the tangible condition.

When two pieces were close enough (i.e. the total distance of the two corresponding corners was smaller than 20 pixels), and there was a correct fit between these two facing edges, the two pieces would snap together and trigger a correct connection event with the "bing" sound. If the pieces did not fit, they were not be connected. After the connection, these two pieces became a unity and could not be taken apart again. But different from the TUI version, there was no white circle indicating a correct connection. That was because making an incorrect connection in TOUCH was prevented by the system, and once a correct connection had been made, the two pieces could not be separated again. It was assumed that such visual feedback was enough for participants to identify when a correction was needed, thus providing a white circle would be redundant.

The reference image in the TOUCH condition could be controlled in the same way as controlling the pieces. It was also made as 80% of the actual puzzle size and could not be scaled.

The design of the TOUCH puzzle allowed users to use an unlimited number of fingers to manipulate the pieces, thus supporting bimanual direct interactions. Such direct manipulations and the snapping effect emulated simple physics rules. The screen size was expected to be large enough to leverage a users' body awareness and skills, but not too large to exceed the reach of normal adults.

The similarities and differences between TUI and TOUCH are concluded in Table 4.1.

Table 4.1: Similarities and differences between TUI and TOUCH puzzle

	TUI	**TOUCH**
Tactile feedback	Yes	No
Manipulation space	3D	2D
Connectivity	Physical connection	Digital snapping
Visual feedback	White circle	Snapping effect
Resolution (pieces)	High	Low
Audio feedback	"Bing" sound	
Specialized device	Yes	N/A
Space-multiplexed	Yes	
Support bimanual actions	Yes	

4.6 Setting

The study was conducted in the BioMedia and Tangible Computing Lab (Room 3930) at Simon Fraser University, Surrey. The room was quiet for video recording with no interruptions. Participants stood on one side of the digital tabletop, while a video camera was set up on the other side of the table to record their actions, as illustrated in Figure 4.8.

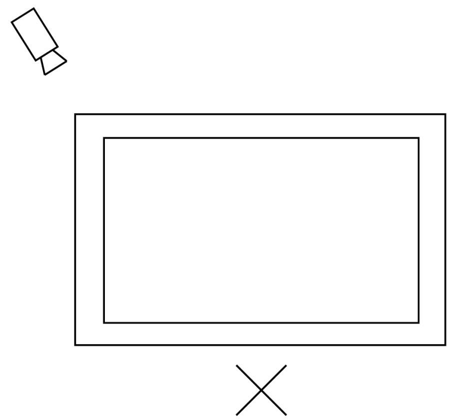

Figure 4.8: Overview of the study setup. The cross sign indicates where the participant stands.

4.7 Assumptions

The three major differences between TUI and TOUCH were the manipulation space (3D vs. 2D), the visual feedback (a white circle vs. the snapping effect) and the tactile feedback (present vs. absent). It was assumed that by using the study design, these three factors could be isolated from the others (i.e. the puzzle theme, the size of the pieces, the number of pieces, and the availability of the reference image).

The order in which a participant used the two interfaces was assumed to affect both the performance and preference. Since there was only a short practice session intended to introduce the usage of the system, and not a complete warm-up trial, the first task might help participants develop a more efficient strategy for the second task, resulting in faster completion and more comfort with the second interface. This factor was taken into account by balancing the order that both TUI and TOUCH were used in each session.

For the visual feedback of a correct connection, a white circle was not provided in the TOUCH puzzle because it was assumed that the snapping effect was adequate to provide similar visual feedback as the white circle in the TUI puzzle.

It was also assumed that participants' previous experience with the touchscreen interface and the jigsaw puzzle might affect their performance, strategy, and preference. For example, those who owned a touchscreen cell phone were likely to use it everyday while those who didn't have one might barely use it; those who played with jigsaw puzzles a lot might have better developed strategies than those who had not played for a long time. So these factors were also considered by collecting information using a pre-questionnaire.

4.8 Participants

Sixteen participants were recruited for the main study. The participants were recruited from graduate and undergraduate students at Simon Fraser University Surrey campus via an online participation pool system hosted by the School of Interactive Arts and Technology. All the participants were recruited without any discrimination other than being fluent in English because they would be asked to give comments at the end of the sessions.

The study used a within subject design and was fully balanced with interface styles (TUI and TOUCH), puzzle themes (pirates and witches), order (TUI first or TOUCH first) and participant gender. Each participant was asked to complete one puzzle task in each condition (TUI and TOUCH), so two tasks in total.

In order to balance puzzle themes and interface styles, there should be four groups as shown in Table 4.2. Thus the sixteen participants were randomly assigned to these four groups with the exception of gender balancing.

Table 4.2: The arrangement of sixteen participants to balance between gender, order, puzzle themes and interface styles.

	TUI-TOUCH	**TOUCH-TUI**
TUI:Pirate Theme, TOUCH:Witch Theme	2 females, 2 males	2 females, 2 males
TUI:Witch Theme, TOUCH:Pirate Theme	2 females, 2 males	2 females, 2 males

The sixteen people who participated in the main study were each given a $20 gift card as remuneration.

4.9 Main Study - Procedure

The main study consisted of sixteen single-participant sessions, each involving solving two jigsaw puzzles. The investigator was present during all the sessions.

Prior to the study, participants were given a consent form to read and sign, and were informed about the goal of the study and the task they would be required to complete. They were informed that there was no time limit for the tasks and they were free to quit anytime. They were also asked to fill out a pre-questionnaire.

At the beginning of each puzzle task, an introduction to the interface was given to the participants.

For TUI, they were told that they needed to physically connect the pieces. If a correct connection was made on the tabletop, a white circle would be shown beneath the junction and a “bing” sound would be played, otherwise no feedback would be given. They were also told that they could translate or rotate the reference image by using the physical block. If the block was removed from the tabletop, the reference image would not disappear. However, the reference image was not resizable.

For TOUCH, participants were told that they could move the pieces and the reference image by one- or two-finger dragging, or rotate them with two-finger panning. Neither the pieces nor the reference image was resizable. The connection could be made by dragging the two edges that might fit closer to each other. If they fit, the system would snap them together automatically and play the “bing” sound, otherwise the connection could not be made.

After the introduction, participants were given a practice session with the castle puzzle so that they could get familiar with the operations on the first interface they were about to use. The practice session ended when they had made more than two correct connections or indicated that they were ready to start the formal study.

Then they were given the puzzle for the first interface to start solving it. The video recording started at the same time.

After the first puzzle was completed, the participants were asked to take a short break while the investigator getting ready for the second task with the second interface. There was also an introduction, and a practice session for the second task, using the castle puzzle. When both puzzles were completed, the video recording was stopped and they were given a post-questionnaire to fill out. After that the whole study was completed.

The detailed study protocol and verbal script are included in Appendix C.

The main study was designed to gather data about the participants’ performance, strategy and preference on the tangible and the multi-touch interfaces. The measurements of the main study are introduced in Section 4.10. The data analysis is discussed in Chapter 5.

4.10 Measures

The study was designed to collect both quantitative and qualitative data, including videos, questionnaires and observation notes. The majority of the quantitative data that were used in the statistical tests was obtained by coding the video records of the sessions. The answers to the questionnaires and observation notes were used to assist the interpretation of the statistical test results.

As stated in the research question, three aspects of the puzzle solving process needed to be investigated: users' performance in TUI and TOUCH; users' puzzle solving strategy while using TUI and TOUCH; and users' subjective preference of the interfaces. All the three aspects were measured by a mix of quantitative and qualitative data. In addition, demographic data was also collected by using a pre-questionnaire. The relationship between research questions and measures are presented in Table 4.3.

Table 4.3: The relations between research questions and measures.

Research Question	**Measures**
RQ1: Performance	Completion time Total count of actions
RQ2: Strategy	Duration of each action Count of each type of actions Temporal sequence of actions Participants' self-report Observation notes
RQ3: Preference	Open and closed questions
Demographics	Closed questions

4.10.1 Performance

Users' performance was measured by the completion time and the total count of actions used in each task. Task completion time was computed as the total duration of a participant's on-task activities solving each puzzle. By using video coding, the on-task activities were split into a sequence of mutually exclusive events, so the total count of user actions could be calculated. The completion time and the count of actions were used to evaluate the efficiency of the interfaces.

4.10.2 Puzzle Solving Strategy

The puzzle solving strategy was analyzed quantitatively by the duration of each action, the count of each type of actions, the actions' temporal sequence, and qualitatively by participants' self-report in the post-questionnaire and investigator's observation notes for each puzzle task.

The information about actions was determined by video coding. All actions or events in the puzzle solving process were categorized into six action/event types, which were *direct connection (DC)*, *indirect connection (IC)*, *exploratory action (Ex)*, *adjustment action (Ad)*, *on-task-non-touch event (ONT)* and *off-task event (OffT)*. The start and end time of each action/event was recorded.

Participants' self reports and the observation notes on their strategies were used to triangulate with the video analysis results.

The details of the video coding method are given below.

Action

An action is the base unit for coding user behavior. It describes a certain segment of user behavior. Its definition varies among different types of behaviors.

1. For direct and indirect connections, exploratory actions, and adjustment actions that have a single target (either its an individual piece, a group of connected pieces, or the reference image), an action is defined as starting from the moment a participant touches the target until the target is let go. If a participant holds two or more pieces in their hand simultaneously, the action is defined by attention instead. That is, the action starts on a piece when the participant starts attending to it and ends when the attention is gone. The majority of actions are of this type.

2. For adjustment actions that have multiple targets, e.g. when participants quickly spread a pile of pieces to find a particular one, an action is defined as starting from the moment the participant begins the series of actions, until they start another type of action.

3. For on-task-non-touch actions, an action is defined as the duration when a participant is focusing on the task but not touching any object.

4. For off-task actions, an action is defined as when a participant starts an action that is irrelevant to the task up to the time they resume the work on the task.

Each action class is defined as follows.

Direct Connection

Direct connection (DC) is when a participant mentally determines where a piece fits and physically manipulates the piece(s) only to connect it, which does result in a correct connection. A prototypical situation is when a participant picks up a piece and connects it without any hesitation. The connection serves only to bring the participant closer to the goal but does not offload any mental activity, so it is *pragmatic* and *non-complementary*. Direct connection requires the participant to have a clear mental image of where the piece fits. Thus by measuring the count of direct connections, the problem solving operations that are predominately mental rather than complementary can be identified.

Indirect Connection

Indirect connection (IC) is when a participant physically manipulates a piece in order to determine where it will fit and ends up with a correct connection. In this case, the participant offloads some of the mental activity of determining where a piece fits by physically modifying the environment, so it is a *complementary action*. The action itself also brings a piece into the correct location, so it is an *pragmatic action* too. Prototypical examples include holding a piece to visually compare it to a shape or pattern on the reference image, or to another piece to determine fit. How well an interface supports offloading pragmatic mental activity can thus be evaluated by measuring the frequency of indirect connections.

Exploratory Action

Exploratory action (Ex) is when a participant physically manipulates the piece(s) to explore where it might fit on the puzzle or organizes the puzzle space, but does not end up with a correct connection. Examples include making piles of like pieces such as edges and corners, or pieces having similar patterns.

Such actions recruit external elements (i.e. physically manipulating or organizing the pieces) to make the future solving easier but do not bring the user any closer to the completion of the puzzle, so exploratory actions are *epistemic* and *complementary actions*. Most exploratory actions can be identified by this rule, although some of them may be difficult to tell because the benefit plays out later.

In terms of complementary/non-complementary and pragmatic/epistemic, the relations between direct connection, indirect connection and exploratory action can be summarized as shown in Table 4.4. Direct and indirect connections are the only types of actions that can bring participants closer to the completion of the puzzle, thus they are both pragmatic. Exploratory actions do not lead to any correct connection, instead, they may give the player a more comprehensive understanding of the puzzle, or change the puzzle in some way that may lead to an easier solution, so they may be epistemic. Indirect connections and exploratory actions are the only action types that recruit external resources to reduce cognitive load in order to solve the problem more efficiently, so together they constitute the category of complementary actions.

Table 4.4: Categorizing three major action types by complementary/non-complementary and epistemic/pragmatic.

	Complementary	**Non-complementary**
Pragmatic	Indirect connection	Direct connection
Epistemic	Exploratory actions	N/A

Adjustment Action

Adjustment action (Ad) is when a participant quickly manipulates one or more pieces or reference images around in order to further task goals immediately. Prototypical examples include quickly spreading a pile of pieces, and moving the reference image to a more comfortable position on the screen.

On-task-non-touch Event

On-task-non-touch event (ONT) is when a participant stops touching any object on the screen for a certain period (the threshold was set to two seconds in video coding) but is still attending to the task.

Off-task Event

Off-task event (OffT) is when a participant temporally switches to non-task related affairs (e.g. answering a phone call). This part of time was excluded when calculating completion time.

4.10.3 Preference

Participants' subjective preferences about the interface styles were collected in the post-questionnaire using three questions:

1. Which interface is more preferable and why?
2. Which interface is easier to use and why?
3. Which interface is more enjoyable and why?

They were also asked with three open-ended questions on whether they wanted to do anything but couldn't when using the two interfaces, and if they felt themselves used different strategies with the two interfaces.

The post-questionnaire used in this study is attached in Appendix B.

4.10.4 Demographic Variables

At the beginning of each session a pre-questionnaire was given to the subjects to collect demographic information, including gender, age, dominant hand, and his/her experience with touchscreen devices and jigsaw puzzles (on a one to seven scale, with one as novice and seven as expert). These factors were later used to determine if they were correlated to participants' performance or strategy.

The pre-questionnaire used in this study is attached in Appendix A.

Further details of video coding, statistical analysis and qualitative analysis will be provided in Section 4.11, Section 4.12 and Section 4.13.

4.11 Video Coding

Video records of the main study sessions were each coded into a sequence of mutually exclusive actions using Noldus Observer XT 7.0, including the start and end time of the action and its type. A video coding scheme was developed based on the definitions of the action types described in Section 4.10. To achieve a satisfactory inter-rater reliability, four segments of video were randomly chosen and coded individually by three raters until the inter-rater consistency had reached 75%. Then 20% of the videos (i.e. 6 out of 32 sessions) were coded individually by two raters, the inter-rater consistencies were all above 75%. Finally the rest 80% videos (i.e. 26 sessions) were coded by a single rater.

4.12 Statistical Analysis

The video record of each session was coded as a sequence of actions stored in a text file. Each action was labeled with the action class, and the start and end time. So each discrete action had a duration and could be counted. These text files were then analyzed using a Python script to calculate the times of appearances and durations of actions. The result was exported to JMP for statistical analysis. Participants' answers to the demographical questions, their previous experience with touchscreen devices and jigsaw puzzles, and their preference of the interfaces were gathered from the pre- and post-questionnaires. This data was analyzed with descriptive and inferential statistics as follows.

4.12.1 Calculating Measures and Descriptive Statistics

Performance

The absolute or total completion time (CT) spent on each action class was the sum of the completion time spent on all the actions in the category. The notation used was: direct connection (CT_{DC}), indirect connection (CT_{IC}), exploratory action (CT_{Ex}), adjustment (CT_{Ad}), on-task but non-touch (CT_{ONT}) and off-task (CT_{OffT}).

The total completion time ($\mathrm{CT_{total}}$) of the session was then calculated as:

$$CT_{total} = CT_{DC} + CT_{IC} + CT_{Ex} + CT_{Ad} + CT_{ONT}$$

Based on the video coding result, the total count of task-related actions or events ($\mathrm{CA_{total}}$) was calculated by summing up the count of each action class, where CA denotes count of actions in a class:

$$CA_{total} = CA_{DC} + CA_{IC} + CA_{Ex} + CA_{Ad} + CA_{ONT}$$

Puzzle Solving Strategy

In case there was a significant difference in completion time and count of actions for the two puzzle tasks, relative measures of the time and count were calculated. The relative measures for each action class reflects the time or count proportion of total time or total count for that class. The relative completion time ($\mathrm{RCT_{Act}}$) was calculated as:

$$RCT_{Act} = \frac{CT_{Act}}{CT_{total}}$$

Similarly, the relative count of an action class ($\mathrm{RCA_{Act}}$):

$$RCA_{Act} = \frac{CA_{Act}}{CA_{total}}$$

So the value of $\mathrm{RCT_{Act}}$ represents the proportion of total completion time spent on the action type Act. For example, $RCT_{IC} = 0.20$ means the participant spent 20% of the total completion time on indirect connections. For the relative count of the action, it indicates the proportion of the count of this type of action in the total count of actions occurring in this session. For example, $RCA_{Ex} = 0.4$ means 40% of the total count of actions in this session were exploratory actions.

Since IC and Ex constitute the category of complementary actions in the task, the combined RCT of IC and Ex (i.e. $\mathrm{RCT_{CA}}$) was also calculated, where $RCT_{CA} = RCT_{IC} + RCT_{Ex}$.

The average duration of all actions ($\overline{CT_{total}}$) and each action class ($\overline{CT_{Act}}$) were computed as:

$$\overline{CT_{total}} = \frac{CT_{total}}{CA_{total}}$$

and

$$\overline{CT_{Act}} = \frac{CT_{Act}}{CA_{Act}}$$

The mean value, standard deviation and standard error of $\mathrm{CA}_{\mathrm{total}}$, $\mathrm{CT}_{\mathrm{total}}$, $\mathrm{CA}_{\mathrm{Act}}$, $\mathrm{CT}_{\mathrm{Act}}$, $\mathrm{RCT}_{\mathrm{Act}}$, $\mathrm{RCA}_{\mathrm{Act}}$, $\overline{CT_{total}}$, $\overline{CT_{Act}}$ $(Act \in \{DC, IC, Ex, Ad, ONT\})$ and $\mathrm{RCT}_{\mathrm{CA}}$ were also calculated.

Preference

Participants' preference for interface style was reported by the frequency or the number of participants choosing TUI or TOUCH as more preferable, easier to use, and more enjoyable.

Demographical Variables

The mean value and standard deviation of participants' self-rating of previous experience with touchscreen devices and jigsaw puzzles were reported. An ANOVA was also used to test if there was any interaction between interface style and order, or interface style and gender on the completion time and the count of actions.

4.12.2 Inferential Statistics

Many statistical tests assume that the data used in the test is drawn from a normal distribution. To examine if this assumption was met or not, the Shapiro-Wilks W test was used on completion time (CT), relative completion time (RCT), count of actions (CA) and relative count of actions (RCA). The Shapiro-Wilks W test was chosen because it is recommended for small and medium sample sizes. Table 4.5 shows that the count of exploratory actions ($\mathrm{CA}_{\mathrm{Ex}}$) and the relative count of indirect connections ($\mathrm{RCA}_{\mathrm{IC}}$) had p-values less than $\alpha = 0.05$. ONT's p-values were all less than α. The null hypothesis H_0 (the data is from the normal distribution) was rejected in these results, so the Wilcoxon test would be used instead of the t-test. Using a t-test on the other data is valid because they were from a normal distribution.

Performance

To test the effect of interface styles on participants' puzzle solving performance, completion time (CT) and count of actions (CA) of the two conditions were compared with t-tests.

Table 4.5: The Shapiro-Wilks W test results of completion time (CT), relative completion time (RCT), count of actions (CA) and relative count of actions (RCA) for the task-related action classes. H_0 is rejected in the groups marked with a (*).

	TUI				**TOUCH**			
	CT	RCT	CA	RCA	CT	RCT	CA	RCA
Total	0.308	N/A	0.191	N/A	0.995	N/A	0.064	N/A
DC	0.175	0.863	0.185	0.725	0.715	0.111	0.331	0.059
IC	0.352	0.349	0.416	0.025*	0.228	0.355	0.208	0.034*
Ex	0.417	0.424	0.162	0.907	0.121	0.152	0.004*	0.257
Ad	0.156	0.643	0.258	0.828	0.630	0.131	0.416	0.779
ONT	0.000*	0.000*	0.000*	0.000*	0.005*	0.015*	0.001*	0.001*

Puzzle Solving Strategy

To compare participants' puzzle solving strategies, a series of t-tests were executed on the completion time (CT) and relative completion time (RCT) of each action class across the two conditions. For the count of actions (CA) and the relative count of actions (RCA) that did not meet the normal distribution assumption, the average values were compared using a Wilcoxon test.

4.13 Qualitative Analysis

Besides the quantitative measurements, video coding results were also analyzed qualitatively to discover any interesting temporal patterns. Qualitative data was also collected via observation notes and post-play open questions.

4.13.1 Temporal Analysis

The video coding results were visualized as a sequence of temporal actions. By viewing the sequences for all the sessions, certain temporal patterns could be identified. Patterns included: the trend of occurrence of an action class overtime, clusters of types of actions, and combinations of multiple action classes. These patterns indicated differences of puzzle solving strategies and could be used to help explain the differences regarding performance and preference.

4.13.2 Observation Notes

Observation notes were made about the overall strategy or approach of solving the puzzle and prototypical hand actions during the session. These categorizations of strategies and action classes were subjective to the observer's interpretation. They were used to facilitate interpreting the quantitative results.

Hand action observations focused on the pattern of cooperation between two hands, for example, whether the two hands worked in a symmetric or asymmetric way.

4.13.3 Post-play Questions

Participants' choices of their preferred interface, which was easier to use, and which was more enjoyable interfaces were counted.

Answers to the open questions were summarized to identify common issues that were reported. These answers were later used to better understand the quantitative results and triangulate with the observer's notes.

Chapter 5

Results

5.1 Overview

All the sixteen participants completed two puzzles using the two interfaces. To explore the effect of interface style on participants' performance, strategy and preferences when solving the jigsaw puzzle, both descriptive summaries and inferential statistics were used to compare between TUI and TOUCH conditions. The analysis outcomes are presented in this chapter. This outcome shows the differences and similarities between TUI and TOUCH in terms of the performance and strategy of puzzle solving, and the subjective preference.

5.2 Performance

5.2.1 Descriptive Statistics

Participants' performance in each puzzle task was measured by the total completion time (CT_{total}) of the task, and the total count of actions (CA_{total}). On average, participants spent 20:14 minutes to finish a TUI puzzle and 44% more (i.e. 29:04 minutes) to finish a TOUCH puzzle. They had 194 actions in TUI, 28% less than in TOUCH (268 actions). Table 5.1 and Table 5.2 shows the descriptive analysis of total completion time (CT_{total}) and total count of actions (CA_{total}).

Table 5.1: Descriptive analysis of total completion time (CT_{total}) in minutes.

	N	Mean	S.D.	S. Error	p-value
TUI	16	20:14	6:58	1:45	< 0.01
TOUCH	16	29:04	8:05	2:01	

Table 5.2: Descriptive analysis and significance test of interface style on total count of actions (CA_{total}).

	N	Mean	S.D.	S. Error	p-value
TUI	16	194	74.8	18.7	< 0.05
TOUCH	16	268	97.3	24.3	

5.2.2 Inferential Statistics

A t-test shows that the difference in total completion time (CT_{total}) between TUI (M=20:14 min, SD=6:58 min) and TOUCH (M=29:04 min, SD=8:05 min) was statistically significant ($t(15) = 3.31$, $p < 0.01$).

The difference in the total count of actions (CA_{total}) between TUI (M=194, SD=74.8) and TOUCH (M=268, SD=97.3) was also statistically significant ($t(15) = 2.41$, $p < 0.05$).

5.2.3 Summary

Participants took shorter time and less actions to complete the TUI puzzle than the TOUCH puzzle.

5.3 Puzzle Solving Strategy

5.3.1 Action Class Analysis

Table 5.3 shows the absolute completion time (CT) of each action type in minutes, their relative proportion of the total completion time (RCT), the count of actions (CA) of each type of actions, and its relative proportion (RCA). CT, RCT, CA and RCA are visualized in Figure 5.1, Figure 5.2, Figure 5.3 and Figure 5.4. The relative completion time (RCT)

Table 5.3: Absolute completion time (CT), average duration of a single action ($\overline{CT}$), relative completion time (RCT), count of actions (CA) and relative count of actions (RCA) of each type of action in TUI and TOUCH.

		DC	IC	Ex	Ad	ONT	TOTAL
TUI	CT (min)	2:49	3:32	11:13	2:34	0:05	20:14
	$\overline{CT}$ (sec)	5.2	10.6	6.2	6.1	6.2	N/A
	RCT	15%	19%	53%	12%	0.4%	100%
	CA	33	20	116	25	1	194
	RCA	17%	10%	60%	13%	0%	100%
TOUCH	CT (min)	6:11	3:07	15:34	3:43	0:30	29:04
	$\overline{CT}$ (sec)	9.4	16.6	5.6	5.9	10.4	N/A
	RCT	23%	11%	52%	12%	2%	100%
	CA	40	11	177	37	3	268
	RCA	15%	4%	66%	14%	1%	100%

and relative count of actions (RCA) for each action class are compared between TUI and TOUCH in order to better understand participants' puzzle solving strategies. The results are presented in Table 5.4 and Table 5.5.

Direct Connection

On average, participants spent 2:49 minutes using the TUI and 6:11 minutes using the TOUCH interface making direct connections. The proportions of total completion time (RCT_{DC}) were 15% and 23% respectively. The difference of the proportions (RCT_{DC}) was statistically significant ($t(15) = 3.01$, $p < 0.01$).

On average, 33 (17%) actions in TUI were direct connections, and 40 (15%) in TOUCH. The difference in proportions (RCA_{DC}) was not significant ($t(15) = 1.0$, $p = 0.31$).

The average duration of a direct connection ($\overline{CT_{DC}}$) was 5.2 seconds (SD=0.8 sec) for TUI, significantly shorter than for TOUCH ($t(15) = 8.2$, $p < 0.01$) which was 9.4 seconds (SD=1.9 sec).

Summary Participants spent a smaller proportion of time on direct connections (DC) using TUI compared to TOUCH. The average duration of direct connections was shorter

Table 5.4: Descriptive statistics and significance test of relative completion time (RCT) for each action type between the two interface styles.

		N	Mean	S.D.	S. Error	p-value
RCT_{DC}	TUI	16	15%	5%	1%	< 0.01
	TOUCH	16	23%	8%	2%	
RCT_{IC}	TUI	16	19%	8%	2%	< 0.01
	TOUCH	16	11%	4%	1%	
RCT_{Ex}	TUI	16	53%	11%	3%	0.89
	TOUCH	16	52%	9%	2%	
RCT_{Ad}	TUI	16	12%	4%	1%	0.99
	TOUCH	16	12%	7%	2%	
RCT_{ONT}	TUI	16	0%	1%	0%	N/A
	TOUCH	16	2%	2%	1%	

Table 5.5: Descriptive statistics and significance test of relative count of actions (RCA) of each action type between the two interface styles.

		N	Mean	S.D.	S. Error	p-value
RCA_{DC}	TUI	16	19%	7%	2%	0.31
	TOUCH	16	17%	6%	2%	
RCA_{IC}	TUI	16	12%	6%	1%	< 0.01
	TOUCH	16	5%	3%	1%	
RCA_{Ex}	TUI	16	55%	13%	3%	0.08
	TOUCH	16	63%	11%	3%	
RCA_{Ad}	TUI	16	13%	5%	1%	0.67
	TOUCH	16	14%	8%	2%	
RCA_{ONT}	TUI	16	0%	0%	0%	0.07
	TOUCH	16	1%	2%	0%	

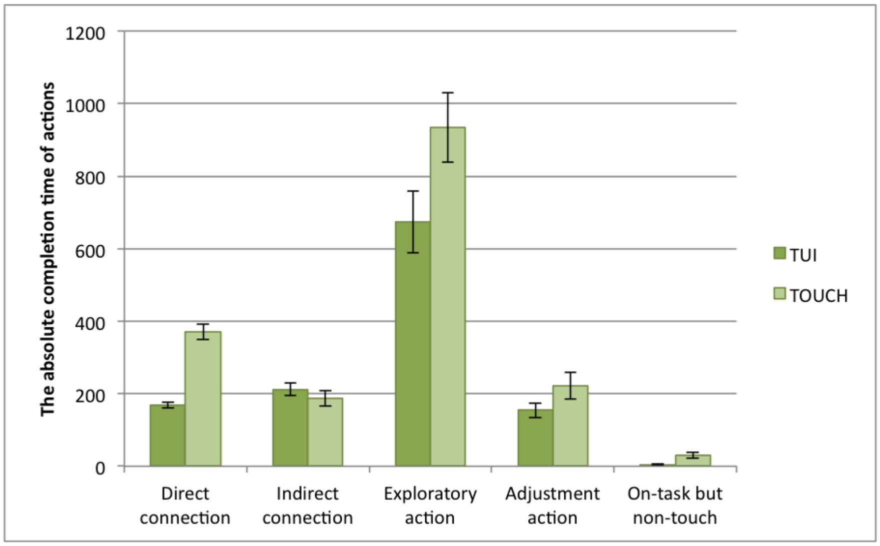

Figure 5.1: The absolute completion time (CT) for each type of action on TUI and TOUCH, in seconds.

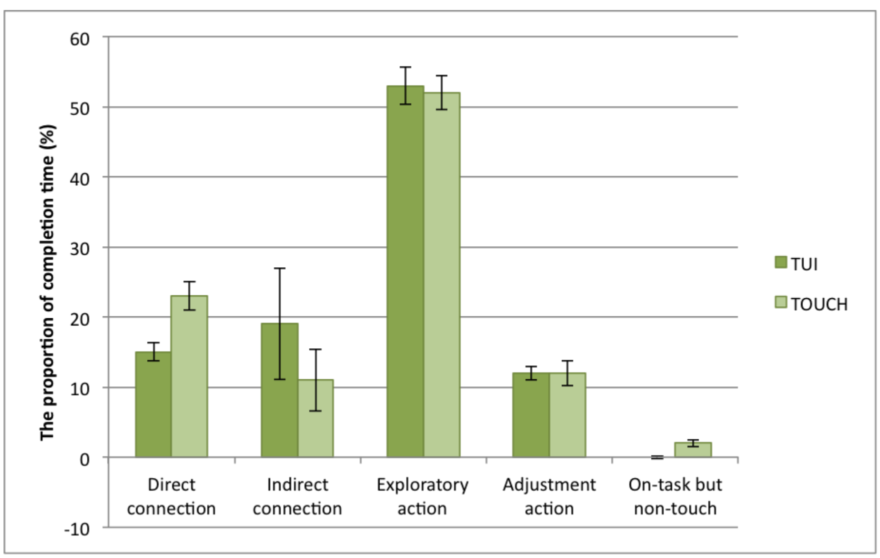

Figure 5.2: The proportion (in percentage) of completion time (RCT) of each type of action on TUI and TOUCH.

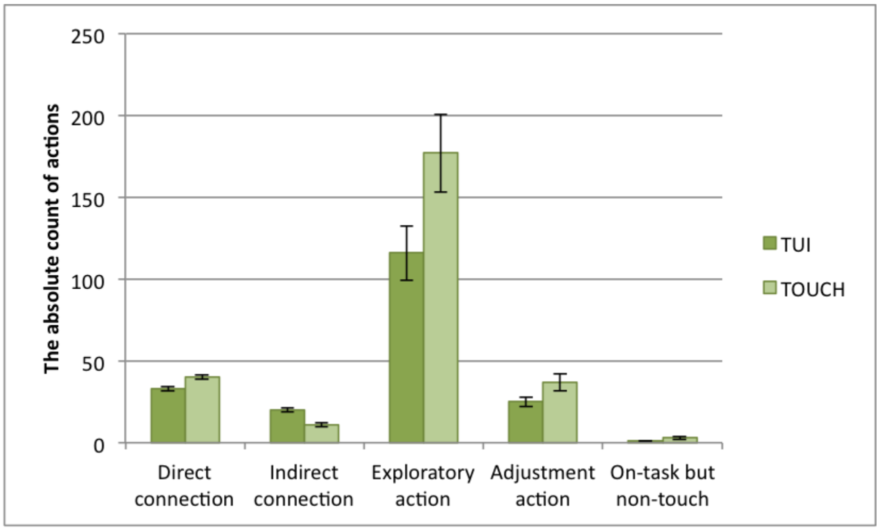

Figure 5.3: The absolute count of actions (CA) of each type of action on TUI and TOUCH.

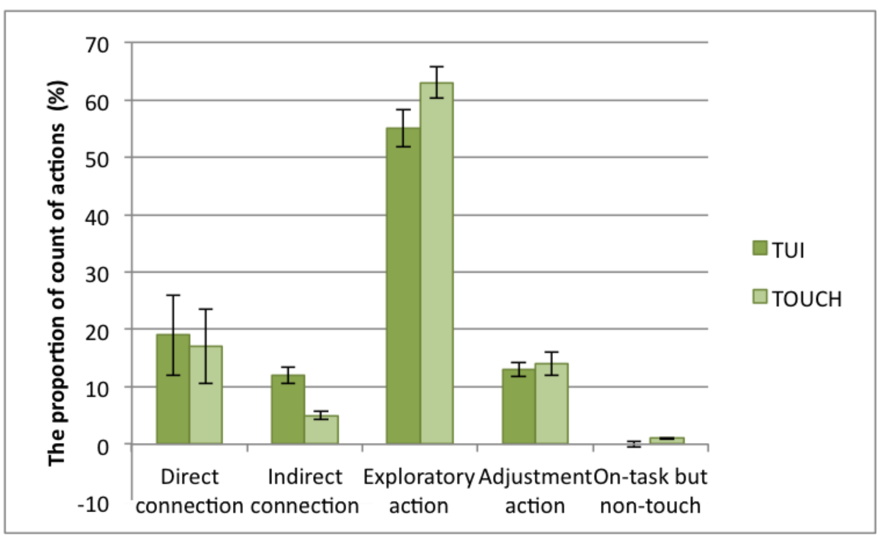

Figure 5.4: The proportion (in percentage) of count of actions (RCA) of each type of action on TUI and TOUCH.

for TUI than TOUCH. However, the proportions of the direct connections in the total count of actions were not significantly different.

Indirect Connection

On average, participants spent 3:32 minutes for TUI and 3:07 minutes for TOUCH making indirect connections. Their proportions in total completion time ($\mathrm{RCT_{IC}}$) were 19% and 11% respectively. The difference of the proportions ($\mathrm{RCT_{IC}}$) was statistically significant ($t(15) = 3.58$, $p < 0.01$).

On average, 20 (10%) actions in TUI were direct connections, and 11 (5%) were in TOUCH. The difference on the proportion ($\mathrm{RCA_{IC}}$) was significant ($W(15) = 367.5, Z = 3.9, p < 0.01$).

The average duration of an indirect connection ($\overline{CT_{IC}}$) was 10.6 seconds (SD=1.9 sec) for TUI, significantly shorter ($t(15) = 7.1$, $p < 0.01$) than for TOUCH, which was 16.6 seconds (SD=2.8 sec).

Summary Participants spent a larger proportion of time and a larger proportion of count of actions on indirect connections using TUI compared to TOUCH. The average duration of indirect connections was shorter for TUI than TOUCH.

Exploratory Action

On average, participants spent 11:13 minutes on TUI and 15:34 minutes on TOUCH, performing exploratory actions. Their proportions in total completion time ($\mathrm{RCT_{Ex}}$) were 53% and 52% respectively. The difference of the proportions ($\mathrm{RCT_{Ex}}$) was not statistically significant. On average, 116 (60%) actions on TUI were exploratory actions, and 177 (66%) were on TOUCH. Such difference in proportion ($\mathrm{RCA_{Ex}}$) was not significant either.

The average duration of an exploratory action ($\overline{CT_{Ex}}$) was 6.2 seconds (SD=1.5 sec) on TUI and 5.6 seconds (SD=1.4 sec) on TOUCH, there was no significant difference here either.

Summary Participants spent a similar proportion of completion time and count of actions on exploratory actions using TUI and TOUCH. The average duration of exploratory actions was similar in TUI and TOUCH, too.

Complementary Action

Combining indirect connection (IC) and exploratory action (Ex), the proportion of completion time spent on complementary actions (RCT_{CA}) on average was 72% on TUI (SD=5%), so higher than TOUCH's 63% (SD=7%), with the difference also being statistically significant ($t(15) = 3.86, p < 0.01$). However the proportions of complementary actions in the total count of actions were similar between the two conditions ($W(15) = 262, Z = 0.06, p = 0.95$). The result is shown in Table 5.6.

Summary Participants spent a larger proportion of completion time on complementary actions using TUI compared to TOUCH. But the proportion of counts of complementary actions was not significantly different.

Table 5.6: Analysis and significance test for relative completion time (RCT) and relative count of actions (RCA) of complementary actions between the two interface styles.

		N	Mean	S.D.	S. Error	p-value
RCT_{CA}	TUI	16	72%	5%	1%	< 0.01
	TOUCH	16	63%	7%	2%	
RCA_{CA}	TUI	16	67%	8%	2%	$= 0.95$
	TOUCH	16	68%	9%	2%	

Adjustment Action

On average, participants spent 2:34 minutes on TUI and 3:43 minutes on TOUCH performing exploratory actions. The proportions of Ad of total completion time was for both 12% and not significantly different. On average, there were 25 (13%) actions on TUI which were direct connections, and 37 (14%) on TOUCH. The difference of RCT_{Ad} was not statistically significant either. $\overline{CT_{Ad}}$ was 6.1 seconds (SD=1.4 sec) on TUI and 5.9 seconds (SD=1.4 sec) on TOUCH, so there was no significant difference. Average durations of the previous four action classes are illustrated in Figure 5.5.

Summary Participants spent a similar proportion of total completion time and total count of actions in Ad actions for TUI and TOUCH.

On-task-non-touch Action

On average, the time spent on on-task-non-touch actions was very short for both TUI and TOUCH, as 5 seconds and 30 seconds respectively. The difference between them was not statistically significant.

5.3.2 Temporal Analysis of Interaction Patterns

By creating temporal visualizations of action sequences for each puzzle task, some interaction patterns were identified.

In both TUI and TOUCH, the frequency of direct connection (DC) increased over time and reached their peak when the puzzle was close to being completed. Such patterns were observed in 12 out of 16 TUI tasks and 15 out of 16 TOUCH tasks. Direct connections also appeared as clusters on the timeline rather than as isolated events.

For indirect connection (IC), due to the relative small amount of occurrence (RCA_{IC}=5%), the change in frequency was not obvious enough on TOUCH, but 9 out of 16 TUI tasks appeared to have an increasing indirect connection (IC) frequency overtime while only two had a descending trend.

Figure 5.6 and Figure 5.7 are examples of the patterns described above. They were extracted from two puzzle tasks of the same participant. In these two figures, each of the six rows from top to bottom represents the occurrence of direct connections (DC), indirect connections (IC), exploratory actions (Ex), adjustment actions (Ad), on-task-non-touch (ONT) and off-task (OffT) actions on the timeline.

Visualizations of all the 32 sessions are included in Appendix D.

5.3.3 Subjective Feedback on Strategy

Participants were also asked if they realized that they themselves used different puzzle solving strategies with the two interfaces. Common answers included:

1. Because the resolution of TOUCH pieces was not as high as tangible pieces, they had to rely more on the reference image to interpret the content of the pieces and determine where they should be placed, while with the TUI pieces the details of the pieces were clear enough.

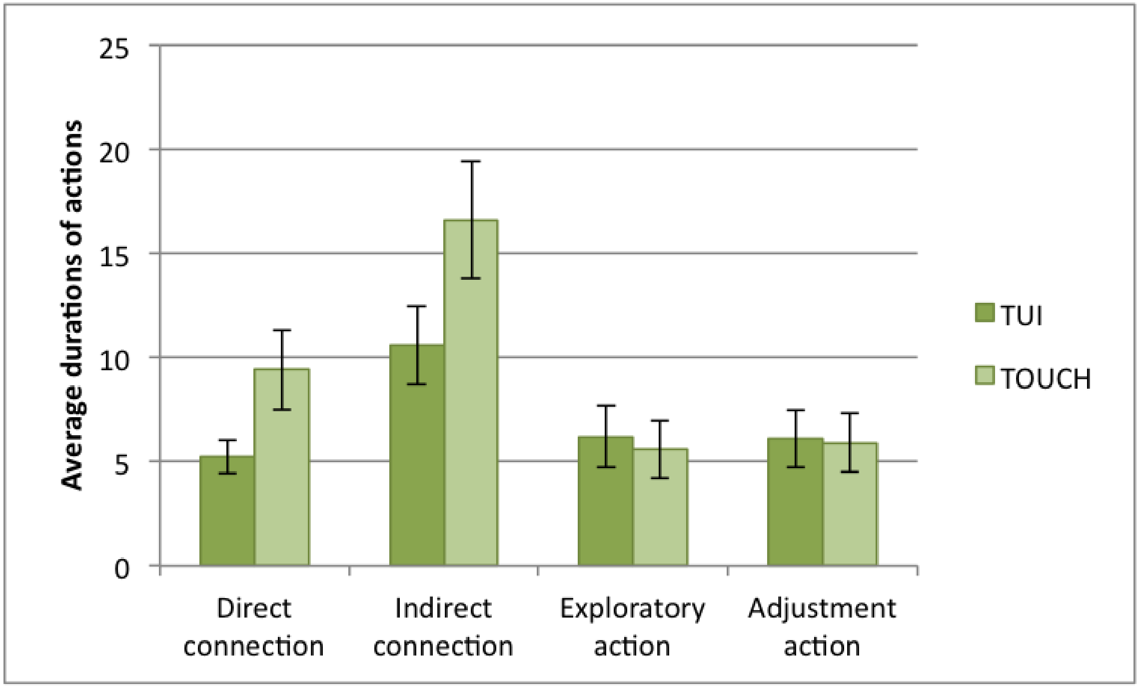

Figure 5.5: Average durations of direct connections, indirect connections, exploratory actions and adjustment actions in seconds.

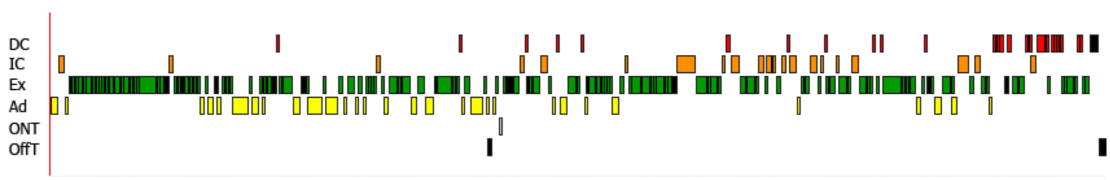

Figure 5.6: A typical visualization of the occurrence of actions over time in a TUI puzzle task. From top to bottom, each row represents DC, IC, Ex, Ad, ONT and OffT.

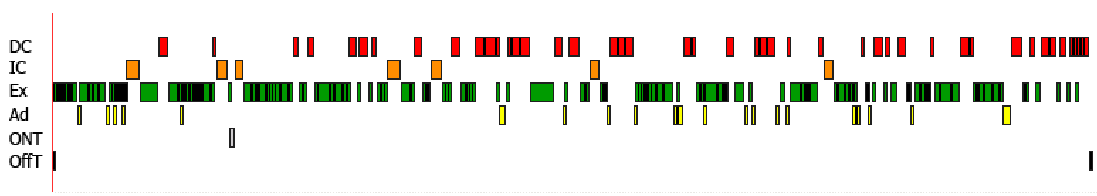

Figure 5.7: The visualization of the occurrence of actions over time in a TOUCH puzzle task. From top to bottom, each row represents direct connection (DC), indirect connection (IC), exploratory action (Ex), adjustment action (Ad), on-task but non-touch (ONT) and off-task (OffT).

2. Because it was more difficult to find a piece in TOUCH, they were inclined to choose from the top pieces on a pile they worked with, rather than searching for a specific piece they had in mind. Or alternatively, they would spend more effort to sort the pieces and keep them organized, so they could be found more easily when needed.

3. With TUI puzzles, they were able to move the pieces close to the reference image to compare, but this approach was not so effective since in TOUCH the piece itself would block the reference image beneath it.

5.3.4 Qualitative Observations on Strategy and Behavior

Outcome of qualitative observations were also concluded from observation notes. This data mostly focused on identifying the overall strategies of solving the puzzle, and any interesting patterns of users' behaviors.

Strategies

There were three common strategies for solving the puzzle: starting with the frame then filling the inner part; starting by building regions that had obvious patterns (e.g. a blue whale in front of a red ship or an orange dinosaur laying on the grass); or simply starting from the bottom of the image and moving upwards. Generally, only four participants used obviously different strategies for the two puzzle tasks, while the others chose similar approaches for both interfaces.

Participants frequently used the third dimension of space in TUI. The most common way was lifting the pieces off the tabletop to bring them closer to their eyes for a closer examination.

Four participants made use of the edges of the table to sort pieces when solving the TUI puzzle. They treated the screen area as a working zone, placed only the pieces that they seemed to have a rough idea about onto their locations on the screen, and left the others "standing by" on the edge, as illustrated in Figure 5.8.

In TOUCH tasks, some participants, especially the shorter ones, also used a trick to overcome the restriction of the screen size. They naturally ignored the boundaries of the screen and moved the completed part of the puzzle out of the bottom edge, in order to bring the area they were working on closer to them, as shown in Figure 5.9.

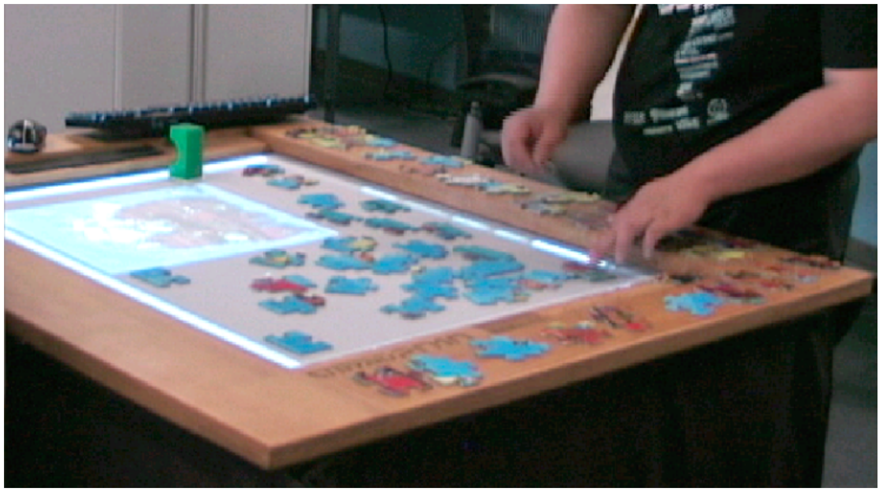

Figure 5.8: A participant was using the table edges as a sorting area.

Figure 5.9: A participant moved part of the completed puzzle out of the bottom edge of the screen.

Bimanual Behavior

Bimanual interaction was observed both in TUI and TOUCH tasks, but was different in nature. Bimanual actions in TOUCH were mostly symmetric, such as using one finger of each hand to rotate or move a piece, or symmetrically sweeping some pieces to the left and right with two hands in order to see the ones beneath them. With TUI, the bimanual actions were more diverse. For example, some participants frequently held multiple pieces in one hand (typically the non-dominant hand), and used the other hand to choose from these pieces and place them one by one on the screen. Some participants used one hand to move pieces out of the way while the other hand placed a new piece in the empty space. When a piece needed to be moved a long distance, some chose to move it by a relay between two hands but not with the same hand, which was the most common choice in TOUCH. In TOUCH, unimanual actions were noticeably more frequent than in TUI, many participants were inclined to use a single hand to perform translations and rotations.

5.4 Preference

Table 5.7 presents the result of post-play ratings given by participants on preference, ease of use and enjoyability.

Table 5.7: The numbers of participants that chose TUI or TOUCH for the three post-play ratings: 1) Which of the two interfaces do you prefer? 2) Which of the two interfaces is easier to use? 3) Which of the two interfaces is more enjoyable to use?

	Preference	Easier to use	More enjoyable
TUI	14	15	7
TOUCH	2	1	10

5.4.1 Preferable Interface

Most participants chose TUI as preferable (14 out of 16). Among 12 who gave their explanations for the choice, eight mentioned TUI was “easier to use”.

5.4.2 Ease of Use

When being asked to choose an interface that they felt easier to use, 15 out of 16 participants chose TUI. The most common reasons for choosing TUI included:

1. The working space was not limited by the screen. Physical pieces could be placed around the screen.

2. It was easier to distinguish among a pile of overlapping pieces and search for a particular one in the pile.

3. By being able to physically pick up and hold pieces in your hand, it was easier to compare two pieces closely.

4. There was no lag on system response.

5. The physical pieces looked more clear than the virtual pieces on the screen because of the resolution.

6. They liked the tactile feedback when connecting pieces.

The reasons that TOUCH was rated as easier included:

1. It was easier to move and connect a large chunk of connected pieces.

2. The snapping effect at correct connections was more effective as a feedback.

5.4.3 Enjoyability

Nine participants chose TOUCH as more enjoyable to use, six chose TUI and the other one chose both.

Participants who rated TUI as more enjoyable did so because:

1. It was easier to use.

2. The tangible puzzle was very similar to traditional cardboard puzzles they had played before, felt more familiar and they were less nervous.

The others who rated TOUCH as more enjoyable explained their reasons as:

1. Using a multi-touch tabletop was a new experience for them, especially playing a jigsaw puzzle on a multi-touch screen.

2. The interaction itself was interesting. It was fun to play by touching.

3. With multi-touch, the solving of the puzzle moved at a “better pace”.

5.4.4 Other Open Questions

Participants were asked to give things that they would like to do but could not when playing the TUI puzzle. Most of them answered that they were able to do everything they wanted with TUI. However, one participant proposed that the visual-audio feedback on TUI could be richer. For example, sometimes it was difficult to realize that a connection was actually incorrect, since it was possible to make wrong connections by pushing the physical pieces together, unlike the TOUCH version where a wrong connection could never be made.

When they were asked about things they could not do with the TOUCH puzzle, the answers can be compiled as:

1. Gestures. They would like to use more natural gestures other than just fingers, such as the ability to quickly relocate a lot of pieces.

2. Better visualization of overlapping pieces (e.g. being able to “see through” the pieces on the top) and using a 3D effect to help sensing the height of a pile of overlapping pieces.

3. Sometimes they might mistakenly touch pieces they did not want to move, for example, when their wrists were too close to the screen and this was sensed as a touch by the screen.

4. The precision of finger touches could be improved.

5.5 Demographic Variables

A total of 16 participants were recruited in the main experiment, 8 males and 8 females. Each participant used TUI and TOUCH in a balanced order to complete one jigsaw puzzle task with each interface. Gender and the use of puzzle themes were also balanced, as shown in Table 4.2.

Fourteen participants were aged between 18 and 30, the other two were 31 or above. All of them were fluent in English and right-handed. Their personal rating of their previous experience with a jigsaw puzzle, on a 1-7 (novice to expert) scale, had a mean value of 3.8 ($SD = 1.4$). Their personal rating of their previous experience with touch screen devices had a mean value of 4.9 ($SD = 1.4$). It can be generally concluded that most of the participants rated themselves as having medium experience with jigsaw puzzles, and the majority of them considered themselves as experienced users of touch screen devices.

Table 5.8: Descriptive analysis and significance test of gender, order and puzzle theme's effect on total completion time (CT_{total}) in minutes.

		N	Mean	S.D.	S. Error	p-value
Gender	Male	8	23:48	7:55	1:59	0.6
	Female	8	25:29	9:34	2:24	
Order	First	16	26:07	8:00	2:00	0.3
	Second	16	23:11	9:20	2:20	
Theme	Pirate	16	24:17	7:53	1:58	0.8
	Witch	16	25:01	9:39	2:25	

Table 5.9: Descriptive analysis and significance test of order and gender on total count of actions (CA_{total}).

		N	Mean	S.D.	S. Error	p-value
Order	First	16	260.0	106.9	26.7	0.1
	Second	16	202.8	69.4	17.3	
Gender	Male	8	238.3	97.7	24.4	0.7
	Female	8	224.6	91.3	22.8	

A series of t-tests were also done with gender, order and puzzle themes groups to investigate if they affected the completion time, but no significant effect was found, as shown in Table 5.8. Also no significant effect of gender or order on the count of actions was found, as shown in Table 5.9.

A significant interaction between interface style and order was found on the completion time by using ANOVA, $F(1, 15) = 5.63, p < 0.05$. This indicates the interface style effect was greater when the TOUCH puzzle was used first (CT_{TOUCH}=30:32, CT_{TUI}=15:50) than when the TUI puzzle was used first (CT_{TUI}=24:37, CT_{TOUCH}=27:36). No interaction between interface style and order was found on the count of actions. No interaction between interface style and gender was found on the completion time and the count of actions.

No significant correlations were found between participants' performance and their personal rating of previous experience with jigsaw puzzles and touch screen devices.

Summary None of the gender, order of interfaces, puzzle theme, and previous experience with touch screen devices and jigsaw puzzles had a significant effect on participants' performance. Only the interface order had an interaction effect on completion time. When the TOUCH interface was used first, the difference between completion times for the two interfaces was larger. However, the ANOVA result had a p-value of 0.05 and the sample size was small, so this result should be interpreted cautiously.

Chapter 6

Discussion

6.1 Overview

This study was designed to explore how tangible and multi-touch interfaces affect the users' experience when doing a spatial problem solving task. The experience was measured in three aspects, which were the performance (i.e. the completion time and the count of actions), the puzzle solving strategy, and the subjective preference. Furthermore, the problem solving strategy was analyzed by looking at the composition of the actions used in the solving process.

As reported in Chapter 5, several differences were found between the two interface styles. TUI and TOUCH had a significant effect on users' performance. As presented in Section 5.2, participants took 43.7% longer to finish the TOUCH puzzles than the TUI ones. It might have been caused by a lower efficiency or effectiveness of TOUCH. A lower efficiency means to finish the same relocation or rotation task, TOUCH took longer than TUI on average. A lower effectiveness means when using TOUCH, participants used a less effective strategy that required more steps or a longer time to think. The first possibility will be discussed in Section 6.2 and the second will be discussed in Section 6.3. Section 6.4 and Section 6.5 discuss the results of subjective preference and the demographical variables. Some design implications will be given in Section 6.6.

6.2 Discussion: Performance

The difference in overall completion time might be caused by the different completion times of the subtasks. There were four types of subtasks, which were direct connection, indirect connection, exploratory actions and adjustment actions. The purpose and approach of the latter three might significantly vary between participants, or between different stages of the solving process. For example, an indirect connection might have consisted of various numbers of translations and rotations with the two interfaces, so it was not comparable between conditions.

But for direct connections, the purpose and the steps were relatively constant between interfaces, which was to direct a piece to its correct location and connect it to the appropriate pieces, during which only a minimum amount of rotations and translations were taken. So by comparing the direct connection completion time between TUI and TOUCH, the efficiency of completing the same unit task with the two interfaces could be compared.

A significant difference was found in that participants took 45% shorter time to finish a direct connection with TUI. This means it took longer to finish the same subtask with TOUCH than with TUI. This finding was consistent with previous studies on tangible and multi-touch interfaces, including the one conducted by Tuddenham et al. where participants took longer to finish a shape matching task with a multi-touch screen than with tangible widgets, because multi-touch had a longer control acquisition time [69]. It is also consistent with another comparative puzzle study conducted by Terrenghi et al. on a table device where participants also took significantly longer to finish a multi-touch puzzle than a physical puzzle, which was considered to be caused by the different interaction modalities (one-hand vs. two-hand) on the two interfaces [68].

As a conclusion, it is possible that TOUCH is less efficient than TUI in hand motor control, which in turn resulted in the longer completion time in TOUCH.

6.3 Discussion: Puzzle Solving Strategy

The possibility that the different performance was caused by the puzzle solving strategies and approaches is also evaluated. The overall strategy can be identified by analyzing the proportion of completion time spent on each type of action, then by comparing between conditions.

6.3.1 Complementary Actions

The comparison shows when making connections, participants spent more time on indirect connections with TUI than TOUCH (19% vs 11%). The larger proportion of indirect connections in TUI indicates that participants more frequently recruited external resources to reduce their cognitive load when working with the tangible puzzles, more specifically, they used an approach that leveraged more physical manipulations to assist mental activities, such as searching for possible connections by actively manipulating and comparing the pieces to reduce the amount of mental calculation. In contrast, participants had to devote more mental effort without the assistance of hand actions when making connections on TOUCH, thus slowing the solving down. This result was also hypothetically proposed by Antle et al. as evidence for the advantage of physical direct manipulations over mouse-based manipulations, although it was not supported by their experiment results [4].

However, indirect connection was only the pragmatic part of complementary actions. For epistemic complementary actions which were the exploratory actions, statistical analysis showed that participants relatively spent the same proportion of completion time (53% for TUI and 52% for TOUCH) and count of actions on exploratory actions (12%) using both interfaces.

Based on the action definitions and the coding scheme, an exploratory action was different from an indirect connection in that it was used to sort or organize pieces but not directly involved in making connections. Apparently the complementary actions used in making connections required a higher speed to follow the pace of mental activities and a higher accuracy to complete the connection. In contrast, sorting and organizing were relatively coarse actions where speed and accuracy were not as important.

From this point of view, one possible interpretation of the result is that TUI and TOUCH were similar in supporting complementary actions that were not directly involved in making connections, for which speed and accuracy were less important. They were both better than a mouse-based interface where few complementary actions were performed [4]. But when more accurate and faster pragmatic complementary actions were needed, TUI was superior to TOUCH, possibly because of its 3D manipulation space and tactile feedback. As a result, TUI was more useful to reduce cognitive load by allowing more pragmatic complementary actions to happen.

According to some participants' feedback when using TOUCH, they had to spend more time organizing the space to keep the pieces in order. So another possible interpretation is that TOUCH had a similar proportion of exploratory actions not because it could well support them as TUI did, but because it compelled users to do so.

6.3.2 Temporal Patterns

As a result of analyzing temporal patterns, the frequency of direct connections became more and more frequent as the solving proceeded in both conditions. When close to completion, they even appeared as clumps. By comparing this to the result reported in the comparative study of tangible and mouse-based puzzles by Antle et al., where the frequency of direct placements was not seen to increase even close to the end of the mouse-based session [4], this result might indicate that in both TUI and TOUCH, participants started to benefit from the epistemic complementary actions they had made, giving them a more clear mental model of the puzzle so as to mentally derive the correct position of the pieces. This provides support for the notion that epistemic complementary actions on both interfaces were effective. Alternatively, it could also be a result of the decreasing amount of unconnected pieces remaining. However the possibility of this explanation seems to be lower since the frequency of direct connections doesn't increase gradually.

6.3.3 Manipulation Space

Because TUI has a 3D manipulation space while TOUCH is only 2D, TUI provides more freedom in the usage space, resulting in higher preference and ease of use. For example, it was possible with TUI to by-pass the restriction of screen size by making use of non-screen spaces (e.g. the edges of the table). Also, by being able to physically lift the pieces, a piece could be brought to a more comfortable distance for closer examination, as stated by some participants "it was easier to compare two pieces closely by holding them in hand". The 3D property also supports a more efficient sense of objects' spatial relations, as mentioned by several participants that it was easier to handle overlapping pieces and search for a particular one in the pile with TUI. Although it is possible to simulate 3D space on a 2D screen using proper visualization techniques, it may not be as effective with tangible objects when handling a large amount of overlapping objects.

The 3D manipulation space also enabled a richer interaction, including various bimanual actions, such as holding multiple pieces in one hand, and using the other hand to choose from these pieces when placing items on the tabletop. These kinds of asymmetric bimanual actions were considered as beneficial according to the Kinematic Chain theory proposed by Guiard and further evaluated by Kabbash et al. [23, 39]. In the case of solving a jigsaw puzzle, these kinds of actions could reduce the need for visual attention or physical acquisition for later use of those pieces. Without a 3D manipulation space, such bimanual actions are restricted to the 2D screen space and simple touching and dragging actions.

The limited 2D space also required participants to organize the working space more carefully to avoid too many overlapping pieces. This was a significant obstacle for TOUCH users and sometimes made the searching for pieces more difficult.

6.3.4 Tactile Feedback

The tactile feedback may have allowed participants to keep a sense of the quantities of objects being held in their hand. With TOUCH the quantity could only be sensed visually, causing a heavier cognitive load than distributing it across two modalities (tactile and visual). This could possibly limit the usage of bimanual actions in TOUCH because when two hands are working together but on different objects, users have to visually keep track of the two focuses of attention, and switch between them. This was also supported by user behaviors according to the qualitative observations: participants barely used asymmetric bimanual actions during the TOUCH tasks, but much more often in TUI puzzles. The same difference was also reported by Terrenghi et al. in their study comparing a multi-touch tabletop and a physical interface [68].

6.4 Discussion: Preference

Most participants chose TUI as easier to use and preferable. Many of the reasons they provided can be attributed to the higher efficiency and effectiveness of TUI, and its similarity to the traditional cardboard-based jigsaw puzzle they were familiar with.

TOUCH was chosen by more participants as more enjoyable. The main reason was that it was a new experience for them to play jigsaw puzzles on a multi-touch tabletop (i.e. the novelty effect).

6.5 Discussion: Demographical Variables

The effects of gender, order and puzzle themes were all examined against the measurements, such as the performance and count of events, but no significant correlations were found.

The self-rating of a previous users experience with jigsaw puzzles did not correlate to the performance either. Also, participants that rated themselves as having more experience with touch screen devices did not perform better or behave more actively in the TOUCH sessions than the novices. But many of them specified in the post-questionnaires that this was the first time they used a (large horizontal) multi-touch device, perhaps the touch screen devices they were familiar with were not of the same kind as the experiment device.

6.6 Design Implications

Based on the findings and discussions outlined previously, the following design implications are presented as the outcome of the study.

Multi-touch interaction is less efficient than tangible interaction

This study was not designed particularly for testing interface efficiency but the user performance in general. However, based on the empirical comparison of direct connection actions and the qualitative data, multi-touch was found to be less efficient than a tangible interface for object manipulation. This suggests that where speed and accuracy take priority, a tangible interface is preferable to a multi-touch interface.

Both multi-touch and TUI can afford complementary actions

Users were able to use complementary actions to help their thinking when using both interfaces. Therefore a multi-touch interface is an advisable alternative to TUIs for tasks that require hand-brain collaboration. But complementary actions are less efficient with a multi-touch interface.

Solving spatial problems with a multi-touch interface requires more organizing activities

Organizing objects in space is usually an important step in spatial problem solving. But a multi-touch interface is less effective because of the 2D manipulation space and the lack of tactile feedback. So, more attention should be paid to design an effective way for organizing objects when a multi-touch interface is used for a spatial task.

The manipulations on both multi-touch and tangible interfaces are effective for forming a mental model

Similar to manipulating tangible objects, manipulating virtual objects with multi-touch is also helpful for forming a mental model of the problem. This could be supported by the increasing frequency of direct connections over time on both interfaces. It also makes multi-touch interfaces a good option over TUIs for spatial problem solving tasks such as urban planning.

Multi-touch relies more on visual feedback

Due to the lower resolution of the screen, users had to devote more effort to recognize the details of the multi-touch display. Although the resolution can be improved by using better devices, many of the common display technologies still have a lower resolution than fine printed materials and physical objects. The lack of tactile feedback on the multi-touch interface applies even more pressure on visual feedback. For example, users could not assess the quantity of a pile of pieces through touch but have to spread them out to visually judge them. Designers should take this into account to avoid overloading the visual modality. In the case of designing a multi-touch jigsaw puzzle, for example, adding contours to puzzle pieces may help users visually distinguish a piece from the others more easily.

What should be tangible and what should be multi-touch?

For hybrid systems such as multi-touch tabletops that have both multi-touch and tangible interfaces, a tangible form may be more suitable for:

1. Input widgets that require high precision and speed. Tangible widgets are more efficient than finger touches, so when precision and speed take priority, such as for a text selection task, a tangible tool may be preferable.

2. Objects that need to be frequently reorganized in space. Spatially organizing virtual objects is less efficient and effective than organizing physical objects, so objects whose spatial information is important, such as the building models in the Urp system [74], should be better in a physical form.

3. 3D objects. Although it is feasible to perform virtual 3D manipulations with a 2D multi-touch screen, using a physical 3D object for such manipulation makes use of everyday bimanual hand skills and has less problems such as occlusion.

Multi-touch may be more suitable for:

1. Objects that need to provide richer visual feedback. Since digital objects can be fully controlled by computers, it is possible to provide richer visual feedback by creating a motion effect (e.g. the snapping effect in the jigsaw puzzle) or a visual effect.

2. Objects that rely more on rigorous constraints. Physical constraints may be easier to understand, but are not as rigorous as digital ones. For example, it is possible to wrongly connect two physical jigsaw puzzle pieces and cause challenges for the problem solving to proceed.

Chapter 7

Conclusion

7.1 Overview

By conducting this exploratory study, the differences between two novel interfaces - tangible user interface and multi-touch interface- were further explored, especially regarding their ability to support the use of hand actions for the purpose of assisting mental activities. The findings showed that in a jigsaw puzzle task, the proportion of epistemic complementary actions was similar on both interfaces, while the tangible interface had a higher proportion of pragmatic complementary actions. Overall, the tangible jigsaw puzzle took a shorter completion time and was preferred.

In conclusion, tangible user interfaces can better enable complementary actions than multi-touch interfaces. The 3D tactile interaction space of tangible interfaces can better facilitate searching, handling, comparing and organizing puzzle pieces, and lead to a faster completion of the puzzle. But manipulations with each interface can lead to the formation of an effective mental model of the puzzle, which enables an more effective problem solving approach. For a problem solving task that does not require a highly efficient and effective strategy, a multi-touch interface may be sufficient and superior since it is easier to implement than a tangible interface.

The outcome of this study contributes knowledge to the development of these two interface styles, especially on digital tabletops where multi-touch and tangible interfaces are often used in combination.

In this chapter, the contributions of the study will be summarized in Section 7.2, the limitations of this study will be discussed in Section 7.3, possible future research directions will be outlined in Section 7.4.

7.2 Contributions

This study explores the differences between tangible user interfaces and multi-touch interfaces in both the motor performance and the cognitive aspects. It uses a theoretical based methodology to analyze user behaviors when doing a spatial problem solving task. The result generated by such analysis uniquely contributes to the understanding of the effect of the two interface styles on users' motor-cognitive activities.

The findings of this study provides evidence to support the idea that tangible user interfaces are more efficient than multi-touch interfaces, and can better support complementary actions when doing a problem solving task. But for spatial problem solving tasks where an efficient and effective solving strategy is not critical, a multi-touch interface is sufficient as an easier-to-implement alternative to tangible interfaces. Based on the findings, several design recommendations are given for designing hybrid tangible and multi-touch interfaces.

In terms of methodology, the data analysis in this study was based on the complementary action theory and previously established empirical work. The methodology looked deeper into the cognitive aspect which was the problem solving strategy, by using relative measures and temporal action analysis, as opposed to only measuring motor skills.

7.3 Limitations

There are several limitations of the study.

First, due to the constraint of the session time, a mouse-based jigsaw puzzle was not included in the comparison. Although this study focused more on the similarities and differences between multi-touch and TUI, a mouse-based condition could serve as a benchmark, as well as to test the advantages of these two novel interface styles over traditional input technologies.

Second, the statistical conclusion validity was limited because of the small sample size of the quantitative collection of data. Sixteen participants did shed some light on exploring the differences in puzzle solving performances and strategies, but the result may not be well generalized onto a broad population.

Third, according to user feedback, the low resolution display of the multi-touch condition caused a significant effect on both strategy and subjective preferences. For example, some users had difficulty interpreting the details of the puzzle pieces on the low fidelity screen, thus they had to switch between the reference image and the pieces to search for a match. This lowered the internal validity of the experiment. A better projector can be used to prevent this problem by narrowing the gap of output quality between the multi-touch and the TUI conditions.

Fourth, this study was not designed specifically to explore the reasons for the difference in efficiency of the two interfaces, (i.e. there was not a breakdown of the manipulation time to response time, acquisition time etc.,) and the coding scheme did not facilitate the recording of unimanual and bimanual interactions. So a more detailed analysis could not be provided in this aspect, unlike some related studies [68, 69].

Fifth, the interactive table used in this study had certain technical limitations in speed and accuracy. It was possible that such limitations also affected the performance, puzzle solving strategy and subjective preference.

Last, the design of the multi-touch interface can be improved, such as adding contours to the puzzle pieces, and implementing sweeping gestures to better simulate the interaction with physical pieces.

7.4 Future Research

Based on the findings of this study, it is evident that a jigsaw puzzle serves as a good context for studying tangible and multi-touch interfaces, so more follow-up research can be done within this context. Here are some possible directions.

Although previous studies have shown that multi-touch is more efficient than traditional mouse-based input [69], explicit evidence is still missing in literature on how the naturalness of multi-touch interfaces makes it superior to mouse-based GUIs from an embodied cognition point of view. This is an important piece when providing solid theoretical support regarding the advantages of multi-touch.

Since this study has provided some exploratory data, following studies can be designed in a confirmatory way, with a larger scale of sample size and multiple control conditions to further investigate the effect of manipulation space degrees as well as different feedback modalities on the interfaces' efficiency and effectiveness. A better implemented interactive tabletop may also be useful to separate out technical limitations from the interface style factor.

It will be helpful too to compare tangible and multi-touch interfaces using a different task such as an urban planning task.

Appendix A

Pre-questionnaire

1. Gender:
   (A). Male; (B). Female;

2. Age:
   (A). Under 18; (B). 18-30; (C). 31 or above;

3. Are you left-handed or right-handed?
   (A). Left-handed; (B). Right-handed; (C). Ambidextrous;

4. How would you rate your expertise on jigsaw puzzle?
   (Expert) 7 6 5 4 3 2 1 (Novice)

5. How would you rate your experience with touch screen devices?
   (Experienced) 7 6 5 4 3 2 1 (Novice)

6. How is your English language level?
   (A). Fluent; (B). Not fluent;

Appendix B

Post-questionnaire

1. Which puzzle did you prefer and why?
2. Which puzzle did you find easier to use and why?
3. Which puzzle did you find more enjoyable and why?
4. Was there anything you wanted to be able to do with the tangible puzzle but couldn't? Please describe.
5. Was there anything you wanted to be able to do with the multitouch puzzle but couldn't? Please describe.
6. Did you notice that you solved the puzzle differently with each interface? Describe any differences you noticed?

Appendix C

Study Protocol and Verbal Script

Time	Action	Description	Data type
5:00	Intro, consent form, pre-questionnaire	Bring the participant to the table-top; Welcome: Introduce yourself You will be playing two trials of jig-saw puzzles today. Before we start, here is the con-sent form of this study. Please read through it carefully. If you accept, please sign here. This is a questionnaire for you to fill out. Please circle the best answer for each question.	Pre-questionnaire
2:00	Intro to the first interface (take TUI as example)	Great. Now we will start the first session.	None

Time	Action	Description	Data type
		In this session, you will use the tangible version jigsaw puzzle. It's very similar to traditional jigsaw puzzles, except that when you connect two pieces correctly on the screen, there will be a white circle show up beneath the pieces, telling you the connection is correct. You will also here a "bing" sound. If the connection is incorrect, nothing will happen. This green block is for the reference image. When you place it on the table, the image will show up. By moving or rotating the block, you can move or rotate the image. But the image cannot be scaled. Demonstrate connecting two correct pieces and two incorrect pieces. Now you will have a short practice session. Please let me know when you're comfortable to start the formal session.	
Up to 5:00	Practice session	Wait until the participant indicates he/she is ready to start.	None
No limit	Session One	Are you familiar with the interface? Ok, you can start the first session now. There is no time limit.	Video, observation notes.

Time	**Action**	**Description**	**Data type**
		Set up the first puzzle. Start video recording and observation note. Leave the participant play the puzzle.	
3:00	Close up	When the puzzle is finished, turn off the video recording. Great. Please take a break, I will set up the second puzzle. Switch interface, prepare for the second condition.	None
2:00	Intro to the second interface (take TOUCH as example)	Are you ready to start the second session? In this session, you will use the multi-touch version jigsaw puzzle. The pieces and the reference image are all displayed on the screen. You can use one or more fingers to drag a piece or the reference image, two or more fingers to rotate it. But again, you cannot scale them.	None

Time	Action	Description	Data type
		If you bring two pieces close enough and there is a fit between them, the computer will snap them together for you, and play a “bing” sound. If the two pieces cannot be connected, nothing will happen. Demonstrate connecting two correct pieces and two incorrect pieces. Now you will have a short practice session. Please let me know when you’re comfortable to start the formal session.	
Up to 5:00	Practice session	Wait until the participant indicates he/she is ready to start.	None
No limit	Session Two	Are you familiar with the interface? Ok, you can start the second session now. There is no time limit. Set up the second puzzle. Start video recording and observation note. Leave the participant play the puzzle.	Video, observation notes.
2:00	Close up	When the puzzle is finished, turn off the video recording. Great. You are almost done!	None

Time	Action	Description	Data type
Up to 10:00	Post-questionnaire	Here is another questionnaire for you, please take a seat and fill it.	
Up to 8:00	Finish	Thank you very much for your participation. Do you have any question for me?	Notes.

Appendix D

Visualization of Temporal Patterns

The following figures show the temporal patterns of action classes in all the 32 sessions.

In each figure,

1. The first row (red) represents direct connections.
2. The second row (orange) represents indirect connections.
3. The third row (green) represents exploratory actions.
4. The fourth row (yellow) represents adjustment actions.
5. The fifth row (gray) represents on-task-non-touch actions.
6. The sixth row (black) represents off-task events.

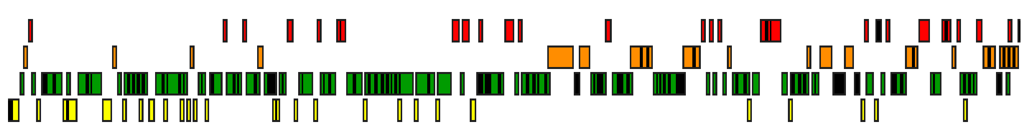

Figure D.1: TUI: 01

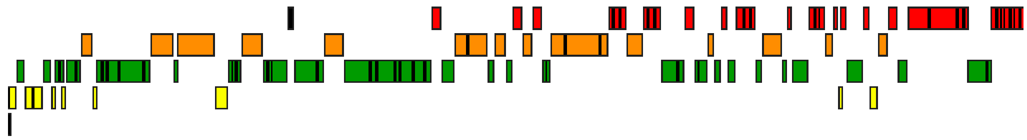

Figure D.2: TUI: 02

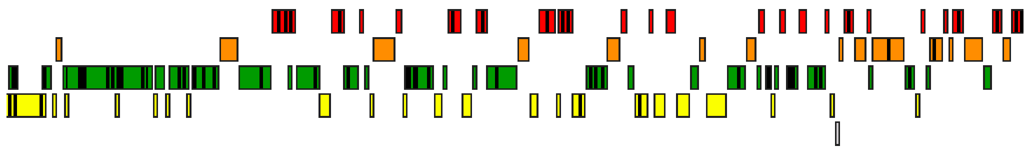

Figure D.3: TUI: 03

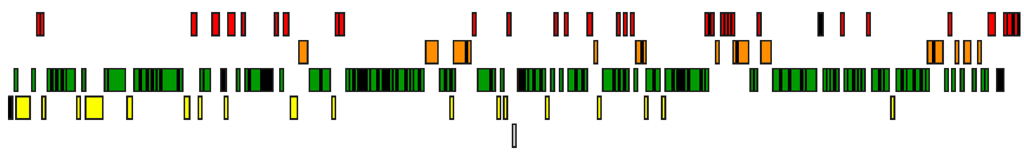

Figure D.4: TUI: 04

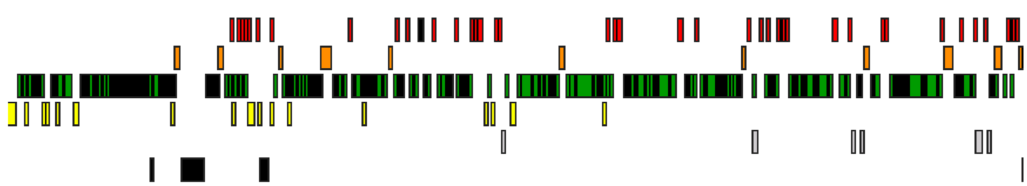

Figure D.5: TUI: 05

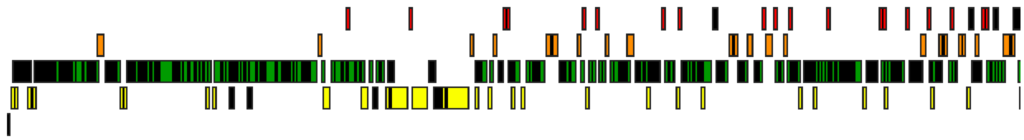

Figure D.6: TUI: 06

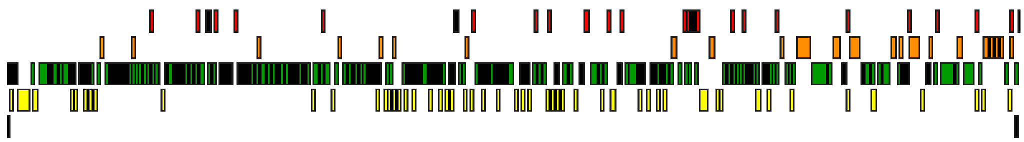

Figure D.7: TUI: 07

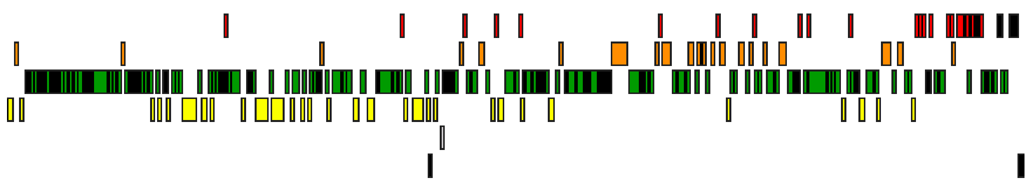

Figure D.8: TUI: 08

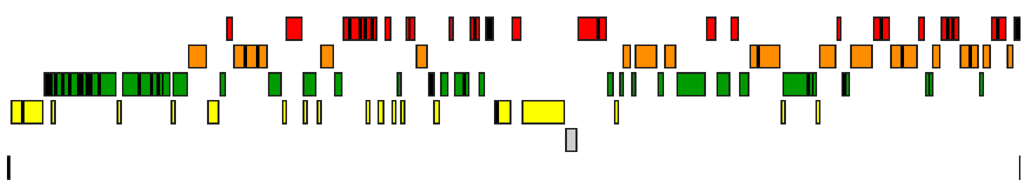

Figure D.9: TUI: 09

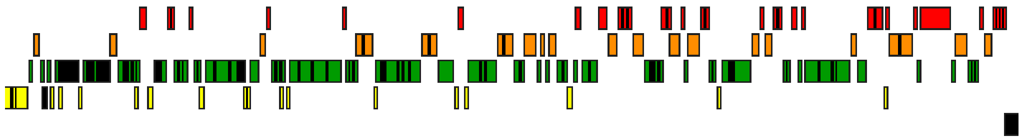

Figure D.10: TUI: 10

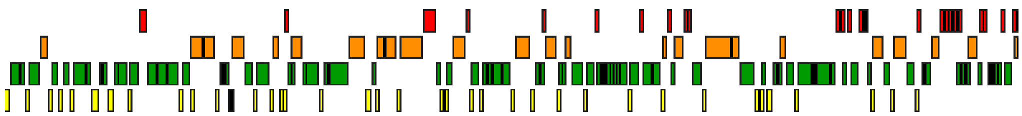

Figure D.11: TUI: 11

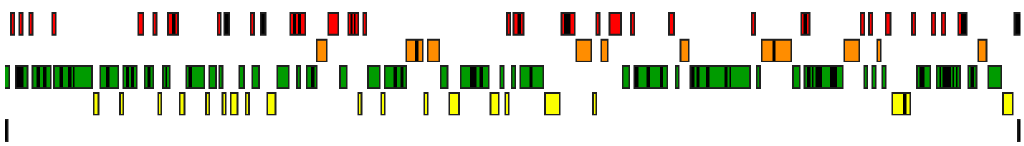

Figure D.12: TUI: 12

Figure D.13: TUI: 13

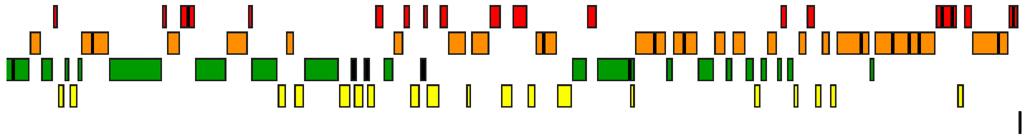

Figure D.14: TUI: 14

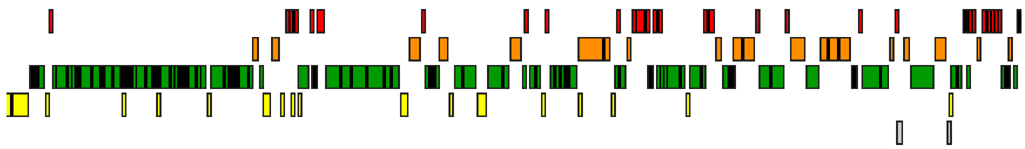

Figure D.15: TUI: 15

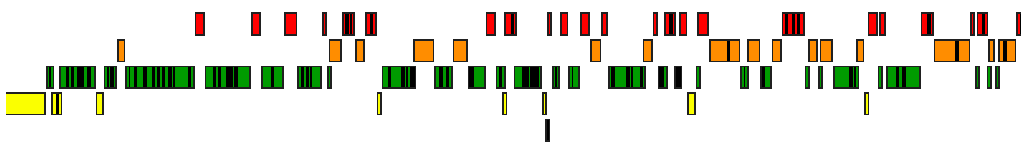

Figure D.16: TUI: 16

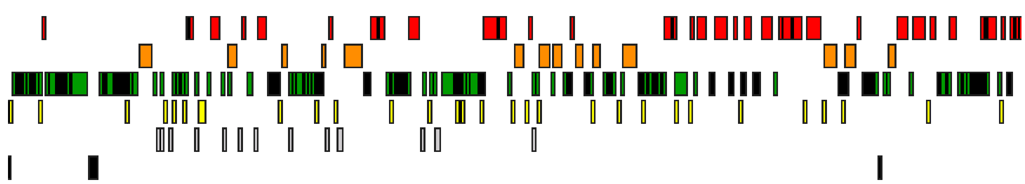

Figure D.17: TOUCH: 01

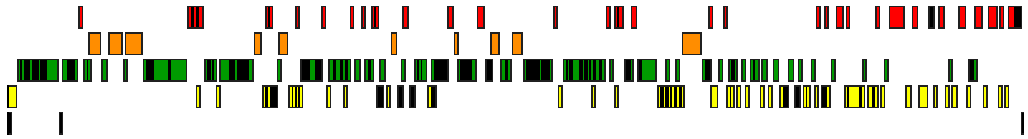

Figure D.18: TOUCH: 02

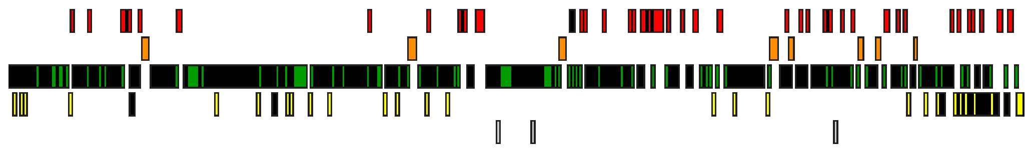

Figure D.19: TOUCH: 03

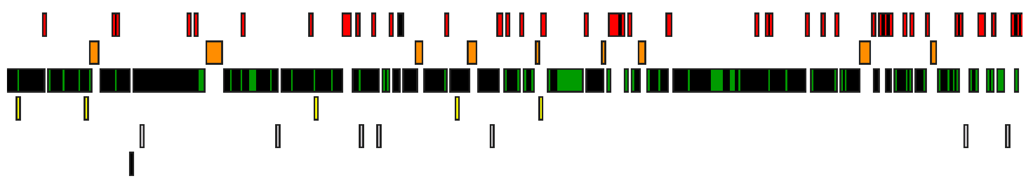

Figure D.20: TOUCH: 04

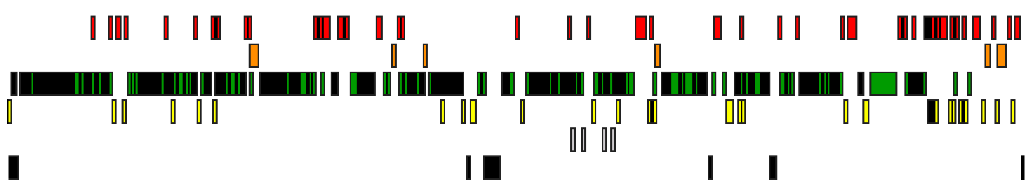

Figure D.21: TOUCH: 05

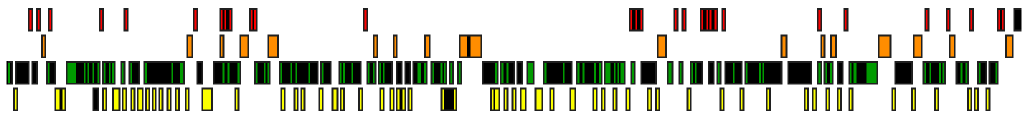

Figure D.22: TOUCH: 06

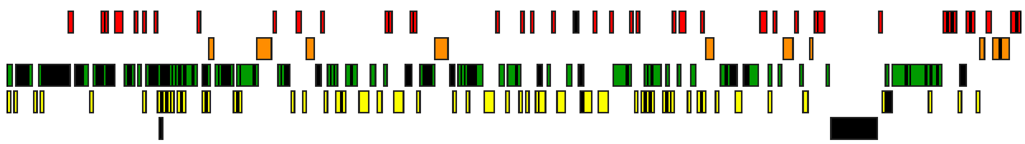

Figure D.23: TOUCH: 07

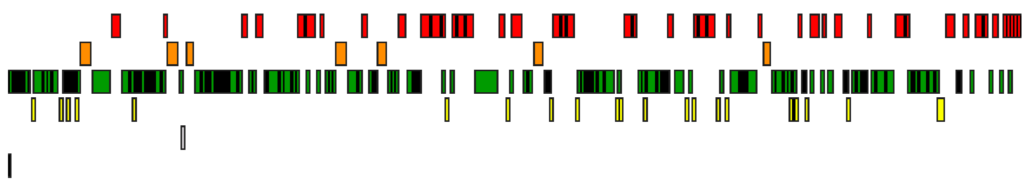

Figure D.24: TOUCH: 08

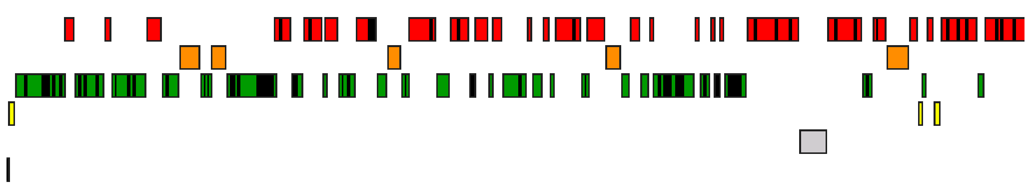

Figure D.25: TOUCH: 09

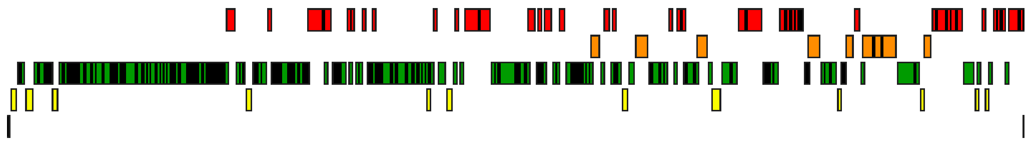

Figure D.26: TOUCH: 10

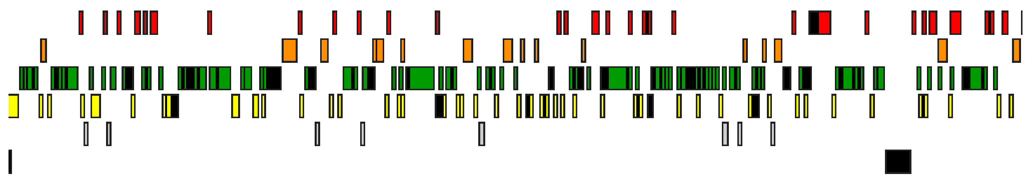

Figure D.27: TOUCH: 11

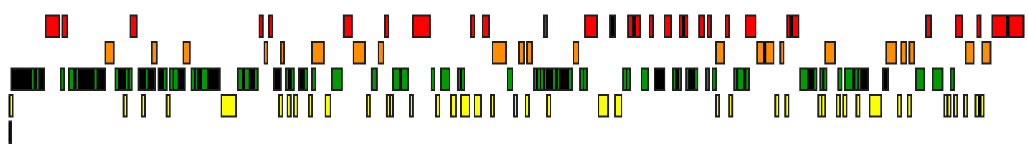

Figure D.28: TOUCH: 12

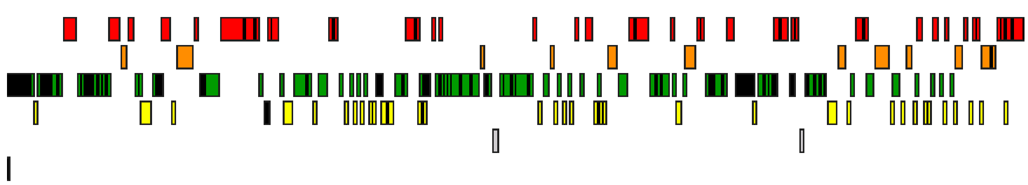

Figure D.29: TOUCH: 13

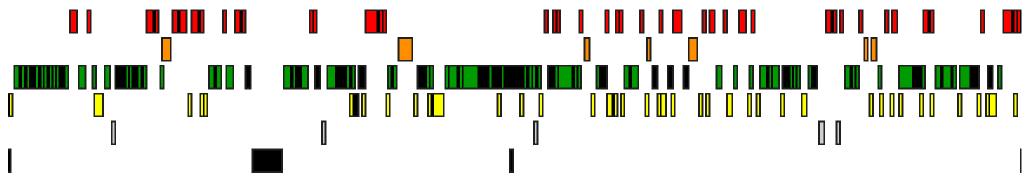

Figure D.30: TOUCH: 14

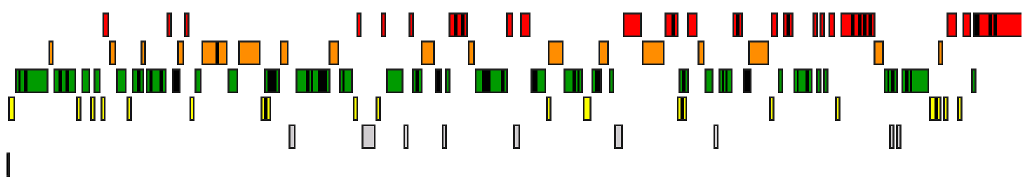

Figure D.31: TOUCH: 15

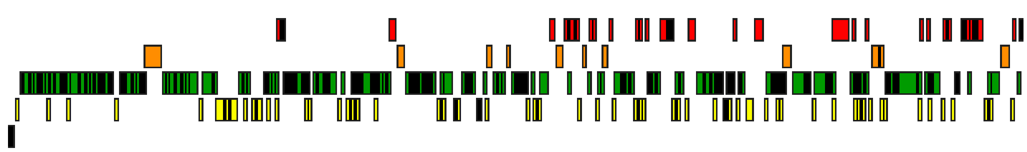

Figure D.32: TOUCH: 16

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