Investigating the Impact of Table Size on External Cognition in Collaborative Problem-Solving Tabletop Activities

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Tables have been used for working and studying for years, and people continue using tables to work with digital artifacts. Collaborative tabletop activities such as planning, designing, and scheduling are common on traditional tables, but digital tables still face a variety of design issues to facilitate doing the same tasks. For example, due to the high cost of digital tables, it is unclear how large a digital table must be to support collaborative problem solving.

This thesis examines the impact of physical features, in particular the table size, on collaborative tasks. This research leverages findings of previous studies of traditional and digital tables, and focuses on exploring the interaction of table size and users' seating arrangement in collaborative problem solving. An experimental study is used to observe the behaviors of two-member groups while doing problem-solving tasks. Two tasks, storytelling and travel planning, were selected for this study, and the experiments were performed on two traditional tables, one small and one large. Although working on digital and traditional tables differs, investigating the impact of physical features in traditional tables can help us better understand how these features interact with workspace awareness and external cognition factors during taskwork.

In the empirical study, external cognitive behaviors of participants were deeply analyzed to understand how physical settings of the table and seating arrangement affect the way people manipulate artifacts in the table workspace. Collaborators passed through different stages of problem solving using varied strategies, and the data analysis revealed that they manipulated material on the tabletop for understanding, organizing and solution making through visual separation, cognitive tracing and piling. Table size, task type and user seating arrangement showed strong effects on the external cognition of collaborators. In particular, the accessibility of sufficient space on the table influenced how much users could distribute their materials to improve workspace awareness and cognitive tracing. On the other hand, lack of space or inaccessible space forced people to use the space above the table—by holding materials in their hands—or to pile materials to compensate for space limitations.

The insights gained from this research inform design decisions regarding size and seating arrangement for tabletop workspaces. For cases in which there is insufficient space, design alternatives are recommended to improve accessibility to artifacts to compensate for space limitations. These solutions aim to enhance the external cognition of users when space is insufficient to work with artifacts in problem-solving tasks.

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Dedication

To Canada,

For giving me the opportunity to see justice, freedom and exemplary human beings in a society.

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Chapter 1
Introduction

Tables are used to support a wide variety of collaborative tasks such as planning, scheduling, brainstorming, design and layout. The height of standard tables is designed to effectively support work with paper and other media while seated. The physical affordances of traditional tables naturally support collaboration; the size of a table allows many collaborators to sit comfortably together in a variety of spatial configurations (e.g. side-by-side, face-to-face). However, as interactive digital tabletop systems become commercially available, key questions remain unanswered regarding the appropriateness of design characteristics for different tasks and user settings. A key open issue that has important ramifications for commercial production and deployment of digital tabletops relates to the usefulness of different table sizes for various required situations.

Because of the physical affordances of tables, a natural goal of digital table design involves understanding how the attributes in the physical design of a table affect collaborative behaviors on digital surfaces. Although different kinds of tables, with a variety of sizes, heights and shapes are commercially available for different situations and users, to date no detailed investigation has been done on the relation between physical factors of a table (traditional or digital), in particular the factor of table size, and human cognition.

This thesis presents findings from a study of tabletop collaboration involving different table sizes, tasks, and seating arrangements to understand the effect of table size on collaborative behaviors. Study findings revealed important differences in how groups used available space on small and large tables, and how they coped with insufficient space. The results of this research can be applied to both the physical design, and the software interface design of digital tabletops.

1.1 Motivation

With technology advances, the artifacts and tools we use are becoming increasingly digitized. Books, photos, papers, and games are now available in digital format, and these digital artifacts are replacing many of the same roles as their traditional media counterparts. People read e-books in bed, play computer games in a shared co-located group, and browse their family photos on a computer. One reason for the success of digital media is the efforts of technologists to make access to digital information easy and to make users feel comfortable when working with digital information. Digital surfaces such as tablets, touch-based smart phones, digital walls and tables are examples of technologies designed to support access to new forms of digital information. However, as a new technology, much work is still to be done to improve the effectiveness of digital surfaces. This thesis focuses on the design of digital tabletops specifically for supporting collaboration.

Commercially available interactive tabletop systems include the Microsoft Surface[1] and the SmartTable[2]. However the appropriateness of each of these technologies has not been investigated extensively for different user contexts. The digital tabletop literature offers some advice on understanding the strengths and limitations of various hardware and software capabilities and distinctive physical form factors for different tasks and user contexts [13] [59], yet few empirical studies exist of these different systems or their design characteristics. As a result, researchers have not yet developed a solid understanding of the many possible system tradeoffs.

A particularly important design characteristic of a tabletop system, which has important ramifications for both vendors and end users, is the size of a table. From the vendor perspective, a smaller table is cheaper to manufacture and deploy, less material and manufacturing space are needed, and shipping costs are reduced. As well, from a technical perspective, providing a high-resolution display – critical for the up-close interactions performed on a table – is significantly easier to provide across a smaller surface. The relatively small sizes of the Microsoft Surface (76.2cm diagonal) and the Smart Table (69.9cm diagonal), for example, offer resolution of approximately 45 dpi using low cost XGA projectors with native resolutions of 1024 x 768 pixels. Providing a larger surface would either result in "fat" pixels, as the same number of pixels are stretched across a wider surface area, or would require a projector array, introducing additional costs and alignment issues. Though tabletop designs incorporating higher resolution (e.g., HD) flat panel displays are on the horizon (e.g., Microsoft recently announced the Surface 2) these displays are still relatively costly. From the user's perspective, a smaller table occupies less space, and would likely cost less given the technical issues associated with larger high-resolution surfaces.

However, a small table may not be appropriate for all user contexts. People may feel "crowded" on smaller tables, and qualitative differences in how people collaborate on large and small tables may negatively impact workflow.

In traditional workspaces people use tables that are significantly larger than their digital counterparts for a variety of collaborative tasks. By categorizing, manipulating and spreading out artifacts, people can display more artifacts on a large table compared to a small table. Such artifact manipulation is defined by Scaife and Rogers [45] as *external cognition behavior* and can be helpful for cognitive processes in

[1] www.microsoft.com/surface

[2] www.smarttech.com

individual and collaborative activities such as problem- solving. Thus, it seems reasonable to assume that a larger table may provide important cognitive, and potentially collaborative, benefits during problem-solving activities. No specific study, however, exists to validate these intuitive relationships. This thesis presents an empirical study to understand how size and the amount of available space on a table impact external cognition behavior during tabletop collaborative problem solving.

1.2 Assumptions on Research Context

Three aspects define a tabletop collaborative problem-solving task, as the name suggests. First, a *problem-solving task* in this thesis refers to tasks aimed to solve problems that do not have a single, concrete solution. These tasks can be mapped to the task classification introduced by McGrath [31]. McGrath identified four main group task processes: generating, choosing, negotiating and executing. The problem-solving tasks investigated in this thesis fall within McGrath's generate process. In particular, he identified two specific types of generate tasks, planning and creativity, where the first involves generating plans and the second involves generating ideas. This thesis includes tasks of each of these types (i.e., travel planning and storytelling, respectively) as representative examples of problem-solving tasks.

Second, the problem-solving task is performed on a table. The table can be a traditional or digital table, and any task activity aimed at solving the problem is performed on or over the table. A typical tabletop problem-solving task deals with some artifacts, digital or non-digital, representing elements of the problem domain. Through manipulation of task artifacts on the table, people try to solve the given problem while sitting, standing or leaning on the table. The number and size of artifacts and the physical features of the table are parameters of the table workspace. People may use the entire surface of the table, or only a part of it to complete the task.

Third, the task is collaborative; that is, more than one person is involved in solving the problem. Because problem-solving activities are often complex, collaboration may help people find a solution in a more efficient and effective way. People may sort, search and try partial solutions together in the table workspace. For the purpose of scoping this thesis research, two-member groups are studied; group size was not considered as an experimental factor.

Given the above definitions, examples of tabletop collaborative problem-solving tasks are tabletop strategic game playing, war games, command and control, and emergency response management (e.g., for earthquake or flood). Note that relationships between the above three aspects are especially of interest. For example, how people use the table workspace individually or in a shared way while they are trying to solve different types of problems is explored in this thesis.

1.3 Problem Statement

Sufficient and effective space in problem solving is believed to aid cognition. Moreover, manipulating artifacts on a table may help team members perform their task activities and collaborate more effectively to solve a given problem. Thus, the research problem in this thesis focuses on the potential of table size to impact external cognition behavior through externalizing representations and manipulating artifacts on a table during collaborative problem-solving tasks.

It is hypothesized that table space will impact external cognition for both individual and team aspects of problem solving. In this research the following two main hypotheses are investigated with this regard:

- *A larger table provides more opportunity to use external cognition during tabletop problem-solving activities*.
- *Supporting external cognition empowers collaboration in tabletop problem-solving in two ways:*
    - *Helping individual cognitive processes*
    - *Facilitating communication and coordination between team members*

1.4 Research Approach and Objectives

The above research hypotheses can be investigated in the context of traditional and digital tables. Although people manipulate artifacts in different ways in each of these contexts, the above research problem applies to both contexts. Thus, results studied in one context are expected to generalize to the other. Furthermore, given the lack of existing digital tables with consistent capabilities available in different size form factors, especially with the specific sizes studied in this thesis, it was decided to study this problem in a **traditional table** context. The research approach of examining interaction behavior on traditional tables for the purpose of informing design choices in a digital context has origins in the literature. For example, traditional tabletop collaboration has been studied to inform the design of remote desktop shared workspaces ([3] and [57]) and to inform the design of digital tabletop workspaces ([36] and [50]). To date, no detailed research about table size, external cognition and collaboration exists on the traditional table. Thus, studying how table size affects these factors on traditional tabletops is a good step toward digital table design.

The thesis explores the research hypotheses by targeting the following objectives:

Objective 1. **Design a suitable testing environment to identify factors influenced by the size of table workspace.** To achieve this goal, a literature review was done and a pilot study was conducted to examine two different table sizes, collaborative problem-solving tasks and seating arrangements. The focus of the pilot study was to examine the number of interactions on and above the table. How participants understand, manipulate and share paper-based media on two different sizes of tables was also considered. This work was done to establish the cognitive and collaborative factors influenced by the amount of workspace available for the empirical study.

Objective 2. **Investigate the effect of identified factors on external cognition.** An empirical study was conducted based on design factors identified from results in the pilot study. An exploratory observational study was conducted, applying three design factors: i) Table size, ii) Task type, and iii) Seating arrangement. A coding schema was created. An in-depth video analysis was conducted on the videotaped study sessions. Field notes, video data, and interview responses were analyzed in detail, by focusing on tabletop external cognition.

Objective 3. **Develop recommendations for compensating size limitations in the tabletop workspace based on findings.** To attain this goal, first existing research efforts on space management in digital tabletop workspaces were analyzed. Then potential solutions that support the use of external cognition were recommended to help compensate for problems associated with limited space in tabletop workspaces.

1.5 Thesis Overview

The remainder of this thesis is organized as follows:

- Chapter 2 presents relevant research in the field of collaborative tabletop problem solving, particularly issues related to tabletop workspaces. The role of the physical features of tabletop workspaces, especially the impact of table dimension on tasks is discussed. This chapter also addresses external cognition, visual search, and awareness (especially workspace awareness).
- Chapter 3 describes the methodological details of the empirical study that investigated traditional tabletop activities. Design factors of the study, the study procedure, and data analysis methodology are presented.
- Chapter 4 presents the results of a quantitative data analysis of the major behaviors related to external cognition in the study.
- Chapter 5 presents the results of a qualitative analysis of major behaviors related to external cognition in the study.

- Chapter 6 discusses the implications of how to apply the study results presented in Chapters 4 and 5, and how these results fit into the scope of the broader literature. Recommendations are proposed related to applying these results to the design of digital tabletop systems.
- Chapter 7 concludes the thesis by indicating how the research goals have been addressed by the presented study and discussing possible directions for future research.

Chapter 2
Background and Related Work

This chapter overviews key concepts and prior work related to research on tabletop collaborative problem solving. People use external artifacts in the tabletop workspace to facilitate thinking, learning and solving problems. Moreover, external artifacts also aid in communicating and collaboration on a table. The research question this thesis aims to address is whether dimensions of the table and artifacts have a significant impact on problem solvers' external cognition and their awareness of the workspace. Therefore, workspace awareness and external cognition are of special interest in this thesis.

This chapter starts with a review of physical features of traditional tables and some observations about how people work on a table. Then two important concepts, external cognition and awareness, are discussed. Their general definitions are reviewed and their roles in a collaborative task are explained.

2.1 Table Workspace

This section highlights table workspace physical features and some characteristics of tabletop activities. It also reviews how previous research has addressed the interaction between table workspace dimensions and taskwork.

2.1.1 Physical Features

A table has several physical features that are important to consider when choosing a table to support human activity, including dimensions and shape. For example, tables come in a variety of heights, lengths and widths. They can also be round, rectangular, semi-circular, or a variety of other geometric shapes. Tables can also have tabletop surfaces that are horizontal or at an angle, such as a table for drafting. In this thesis, I consider only horizontal table, mainly because it is the most efficient for holding artifacts and easy to sit around for people to work. Non-horizontal surfaces may need additional factors to be studied, which are not under consideration here.

Depending on the type of tasks, devices and artifacts people use, the physical features of a table may be adjusted differently. For example, Berquer et al. [2] conducted an ergonomic study to figure out the optimum table height for laparoscopic surgery. They concluded that discomfort is at the lowest level when the table height is as close to elbow height as possible (approximately between 64 to 77 cm above the floor). Similar effects have been considered in working with computers, and ergonomic desks have been extensively designed and provided in the market for this purpose[3]. In other work, Lin et al. [30] conducted a user study to investigate the significance of desk and chair height in Taiwan's schools. They studied different aged primary and high school students to identify requirements of chairs and desks to fit different bodies, and they ultimately proposed some adjustable models for this purpose.

In designing a table, a common range of standard heights is considered, and normally chairs are height adjustable to make the working condition appropriate for a specific person. Of course there are some special tables that are height-adjustable, for instance for working with laptops or drafting.

The required width and length of the table surface depends heavily on the type of work and artifacts that are used on the table. Of course, the arm length and seating position of expected users are also important in specifying the width and length of a table. For instance, Floyd and Roberts [14] discussed seating arrangement and table height in this context from the anatomical and physiological views in ergonomics. They listed principles for designing chairs for maximum comfort and the relation of chair to the table dimension. Dimensions of the table surface (width and length) are often fixed, although there are models that can be expanded, such as tables that have drop-leaves or removable leaves. Digital tables that are currently available do not allow changes to the table surface dimension. But dimension seems important in tabletop activities, as other researchers have noted. For example, Scott and Carpendale [49] investigated territoriality on traditional and digital tables, which is linked to how the table surface is partitioned and is affected directly by the table dimension. Later in this chapter, I elaborate further on the impact of the table surface dimension on tabletop activities.

To limit the scope of this thesis, I did not consider the height of the table in the studies. But it is notable that for tables with sitting height or standing height accessibility would be different, and this factor needs to be studied. In this thesis, the relationship between table's physical features and artifacts representing the given problem is of interest. Because the ultimate goal of this thesis is to propose design guidelines for digital tables, and these tables are often designed in a rectangular shape, the table shape is also fixed to be rectangular.

2.1.2 Taskwork on a Table

A table is probably one of the most common workspaces for doing problem-solving tasks, especially when the process involves some physical artifacts and information. Tabletop taskwork can be decomposed into primitive activities in order to make systematic analysis of the taskkwork easier. Scott et al. [50] list several observed human work practices on traditional tables: sharing objects, assisting each

[3] www.safecomputingtips.com/ergonomic-desk.html

other during workspace activities, partitioning the workspace, transitioning between workspace activities, adapting to the available space, transitioning between tabletop and external work, and using a variety of seating/standing arrangements. In more recent work, Scott and Carpendale [49] highlight the partitioning effect that often occurs when people share a tabletop workspace and the importance of individual and shared territories during tabletop taskwork. Section 2.2 discusses these activities based on human cognitive behaviors, and in the following chapters these will be used to analyze the impact of table workspace on problem-solving tasks.

Digital tables add a new environment for problem solving based on digital artifacts. Studies conducted by Rogers and Lindley [42] showed that digital tables are better at facilitating exploration of ideas (an important factor of problem solving), enhancing awareness, and helping users to engage in teamwork as compared to other computer-based collaborative systems such as interactive whiteboards. Kharrufa et al. [28] also emphasized that a horizontal table surface can be effective in reducing cognitive load and it also enables teamwork in collaborative learning. They conducted a study on collaborative learning of students and recommended some design guidelines to improve externalization (i.e., external cognition).

As discussed in the previous section, the table's physical features can impact the effectiveness of tabletop activities, on either digital or traditional tables. Although working on digital and traditional tables has some differences, investigating problem-solving activities on traditional tables can basically help us understand better how these activities would interact with physical features on both types of tables.

2.1.3 Seating positions around a table

Seating position is also important in collaborative work around table, and previous research has investigated its effect. Tse et al. [58] and Scott and Carpendale [49] point out that seating arrangement impacts how people divide the space to work individually and collaboratively. People's territorial behavior is highly related to how they sit or stand around a table. Note that territories could be temporary and people may change their positions while performing a task. Tang et al. [57] considered seven arrangements, sitting or standing, in studying tabletop collaborative coupling styles. Their findings show that when people want to collaborate more, they tend to be closer to each other. One exception, mentioned by Tang et al., is sitting across a table, which is common position for teamwork and is useful for face-to-face communication during problem solving.

An interesting point has been made by Wallace and Scott [59] about the impact of culture and age on how people work around a table. People from different countries tend to work closer or farther away from each other. This conclusion is originally based on Hall's [18] Proxemics research, which investigated the use of space in human interaction with each other and the environment. According to Wallace and Scott, children prefer to work closely together around a table, and thus a large table surface would not be as appropriate as a small one for a small number of children [59].

2.1.4 The Effect of Workspace Dimensions on Taskwork

Numerous studies have investigated the effect of display size (in general, not necessarily shared displays) on taskwork. Experimental studies conducted by Microsoft Research showed that a large display improves productivity, while causing some negative usability issues. Czerwinski et al. [5] reported that large displays provide several positive effects on cognitive abilities, including recognition memory and peripheral awareness. The former is related to external cognition and the latter relates to workspace awareness, key concepts in this thesis. Tan et al. [56] also mentioned benefits such as better 3D navigation in a large display when doing a task inside a virtual environment.

As mentioned, usability concerns with large displays have also been reported. For example, Robertson et al. [39] reported that in a large display users may lose track of the cursor or they may have problems handling many open windows. Therefore, while visibility of more information at the same time may increase productivity, the complexity and multi-tasking overload may cause some problems. These issues might be also problematic in the table workspace depending on the table size.

In a shared surface workspace, such as a digital table or video wall that is used as a collaborative workspace, spatial organization is important. Normally, personal and shared territories are distinguished in such environments [47]. The workspace size and dimensions may impact spatial organization and might change the behavior of team members in doing their tasks inside both personal and shared territories. Huang et al. [21] discussed properties of large display groupware by highlighting issues related to the personal and group-owned spaces. They pointed out that the larger size of shared large-display workspaces makes artifacts and each user's behavior more visible to users more than in a desktop teamwork environment, which benefits interaction.

Few studies have previously investigated the effect of table dimension on taskwork. Ryall et al. [43] investigated the effect of group and table size on shared-display groupware on different sized digital tables. They used two tables (80cm x 107cm and 76cm x 60cm) for their studies. The selected task was creating poetry using word tiles provided in the digital tabletop interface. Their results showed that table size does not impact task completion speed while the group size did affect completion time. They also found no significant difference in task distribution among group members, as measured by the number of touches for different activities (e.g. picking and dropping word tiles), between the two table sizes.

Interestingly, they noted that larger groups might need multiple displays, including vertical displays, for shared artifacts.

In contrast, Rogers et al. [41] used previous research and anecdotal evidence to conclude that a large table could increase collaboration and awareness because the limited reachability for people around the table requires them to interact more. This conclusion is largely based on experiments conducted by Forlines et al. [15], although their experiments investigated the effect of document size on a table (not the effect of table size). Forlines et al. show that document size has a significant effect on spatial arrangement of documents across a table.

2.2 Task Activities

This section briefly reviews several key concepts–external cognition, awareness, and visual searching–that benefit collaborative taskwork. These concepts are not specific to problem-solving tasks, but in this thesis they are used to investigate different aspects of tabletop problem solving. Moreover, the social forms of these concepts are of special interest in this context.

2.2.1 External and Internal Cognition

The first question is *what is cognition*? There are many definitions of cognition in the literature. For instance, Sharp et al. [52] define cognition as "the activities in our head while we are doing our activities. This includes activities such as learning, thinking, decision making and writing." (page 94). They note that these activities may "abstract, code, categorize, or link data in the problem domain towards achieving specific goals". Norman [33] identifies two types of experiential and reflective cognition observable in human activities, mostly appearing together: *internal* and *external cognition*. Because this thesis deals with collaborative problem-solving activities on tables, the second type is of primary interest. However, without the first type, it is not possible to perform tasks involving the second type of cognition.

The first type is *internal cognition,* in which humans use some internal representation and organization to facilitate processing of given data. For example, people might relate data together or might have a visual memory that allows them to recall places and addresses. In this way, they can remember similar data or relate new things to things that happened in the past.

The second type of cognition is *external cognition*, and as the name suggests, humans utilize the external world to accomplish cognitive activities. The external cognition concept inspired from the *distributed cognition* theory, discussed by Hutchins and his colleagues. Hutchins [23] argued that unlike what thought in traditional cognitive science, cognitive behaviors are not confined inside the human mind. He emphasized that external artifacts and other people play key roles in human cognition. Scaife and Rogers [45] describe external cognition as:

> "… about the ways that humans operate in the world: They are highly resourceful at exploiting their cognitive capabilities, and they do this with a variety of strategies, tools, and representations. This, broadly speaking, is what we refer to as external cognition." (p. 181)

This definition notes that the external cognition is based on external tools and representations that help humans deal with the cognitive challenges of some tasks. For instance, one may use external tools to take a note, mark a calendar, record an interview, use a calculator to facilitate memory recall, or to perform an efficient calculation.

Another definition in the SenseMaking glossary [37] provides more details:

> "External cognition is a phrase referring to ways that people augment their normal cognitive processes with external aids, such as external writings, visualizations, and work spaces. External cognition is human or cognitive information processing that combines internal cognition with perception and manipulation of external representations of information." (online resource)

This definition highlights the distinction of internal and external cognition and how the external form of cognition can help the internal one. External representations of data can be based on paper and/or digital objects in text, voice, video or any understandable format by human.

Another important question is *how do humans benefit from external cognition?* Sharp et al. [52] list three major benefits of external cognition: "*Externalizing to reduce memory load*, c*omputational offloading,* and a*nnotating and cognitive tracing"*. Cognitive tracing is the most pertinent concept to this thesis, and refers to change in the order or classification of artifacts through physical manipulation.

By considering these benefits, we can conclude that external cognition can play an important role in complex activities when humans need to deal with many artifacts, complex computations or data that need to be tracked over time. For example, Andrews et al. [1] note that humans can compare artifacts visually instead of relying on memory or imperfect internal models. They conducted a set of experiments on a large display and learned that the provided space helped people an effective external memory, a semantic layer over the artifacts presented by their orders and clusters, and increasing the efficiency of access to artifacts.

Another notable question in this thesis is *how can external cognition help members in a team?* Is it useful for interaction and collaboration? Does external cognition help team members to follow each other's thoughts? These questions are quite important, and especially significant in collaborative problem-solving activities. The following section deals with the role of external cognition in teamwork.

2.2.2 External Cognition in Collaborative Tasks

When we use external representations of data and knowledge in a form that is understandable for future uses, these formats can also be used by other people[4]. For example, when I put a note on the fridge door to take my daughter to the soccer match, my husband can remind me when he sees the note and tell me we are going to be late. In a workspace, these external representations can be quite important in collaborating and solving problems. Hutchins [23] notes the importance of external cognition factors in a team. Based on Hutchins' work, Gutwin and Greenberg [17] state that *team cognition* may include "using environmental cues to establish a common ground of understanding, seeing who is around and what they are doing, monitoring the state of artefacts in a shared work setting, noticing other people's gestures and what they are referring to, and so on" (p. 1).

As Gutwin and Greenberg point out [17], during teamwork, external cognition often involves communicating with other members and tracking their activities. External cognition relates to workspace awareness, which will be discussed later in this chapter. This form of external cognition is more complex than the individual form, in which only a single person is in charge of cognitive activities and using external artifacts. In a team, a person needs to maintain awareness of what others are doing, decide, and learn and he/she needs to talk to be active in teamwork. This issue is especially important in a problem-solving task. For example, each investigator in a criminal case may follow a piece of evidence and he/she may log or present the findings on a shared board or on a table. All team members need to monitor the changes in the pool of information and how colleagues learn or extract new facts from them.

Another form of external cognition mentioned in the literature is *social cognition*. Susi and Ziemke [55] note a form of social cognition by referring to behaviors in insects. They report that people can affect each other like insects (e.g., ants) when they leave traces behind to help themselves and others. They base social cognition on a link between activity theory and distributed cognition. This effect is observable in collaborative problem-solving tasks. People classify, sort or select artifacts, and their partners track their behaviours in the workspace. By this mean, each individual may join other members in the team to extend an idea or partial solution developed by others.

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[4] Of course the external representation can be coded to meet security and privacy requirements. However, I assume this discussion is focused on trusted team members.

To accommodate the social and external factors in analyzing cognitive activities, Hutchins and his colleagues propose the *distributed cognition* framework. Hollan et al. [20] explain that:

> "Unlike traditional theories, distributed cognition extends the reach of what is considered cognitive beyond the individual to encompass interactions between people and with resources and materials in the environment" (p. 175).

Hutchins lists three kinds of distributions in cognitive processes [22]: i) processes distributed among team members, ii) coordination between internal and external forms of cognition, and iii) processes that are distributed through time. All three kinds of cognitive processes are observable in collaborative problem-solving as well. First, partners may either work on different tasks towards finding the solution, or work together on the same task (e.g. to explore the problem space). Second, there are internal cognitive activities done by each individual, while they also use the external form of cognition. The latter is seen in both teamwork and individual tasks. And third, problem solving has different phases, and team members may use different levels of internal/external cognition and communication in each phase. In user studies, I will investigate these forms of cognitive processes in tabletop problem solving to understand better the effect of physical features on the way participants do the taskwork.

2.2.3 Visual Searching and Browsing Documents (Text/Image)

In a problem-solving task, people may start by either searching or browsing available artifacts. If they do not know what content is available, the initial task would be browsing. As De Bruijn and Spence [6] explain, in browsing people try to overview the available entities to create a rough model of them (e.g. content model for text or image). They refer in particular to a type of browsing, called opportunistic browsing, which refers to how people unintentionally looking for possible options to come up with ideas.

Searching can be defined as a specific type of browsing, when a person knows, even roughly, what she is looking for. De Bruijn and Spence [6] explain that searching is a weighted browsing which tries to answer "is it there?". In their view, people may have a visual or categorical cue of what they are looking for or even a negative categorical cue about a text or image artefact (e.g. find an image that does not include a specific person).

Two aspects are notable in visual searching and browsing: i) collaborative impact, and ii) space and time factors. Scott [47] investigated behaviors of collaborators while they were working in different territories on a table workspace. She observed that people increased the size of storage territories by spreading the artifacts to better search for something during a collaborative design task. Scott also reported that collaborators increased or decreased the size of personal or group territories depending on the task (which sometimes involved searching) or individual/team work. Everitt et al. [13] reported that collaborators (teaching assistants) tended to spread documents as much as possible when working on a table while discussing and editing course materials. Forlines et al. [16] studied the effects of group size and display configuration on visual search. They observed that a group of four had the same performance during a visual search task on one or four vertical displays, although on a single display group members exhibited less independence and more teamwork. The notable point is that displays in their studies are smaller than most of digital tables.

Generally, the lack of sufficient space can lead to spending more time browsing and searching items. De Bruijn and Spence [6] discuss the space-time trade-off in information presentation, which is more visible in small display devices. They proposed a technique, called Rapid Serial Visual Presentation (RSVP), to mitigate this issue. RSVP involves rapidly presenting visual information to users using digital animation techniques [6].

2.2.4 Awareness

As discussed above, external artifacts help people manage memory load and the complexity of cognitive tasks. However, people need to be aware of external artifacts, their changes and corresponding events. Especially in teamwork, changes in the workplace are meaningful and can help team members coordinate their assigned task work. This section briefly reviews the awareness concept and how it helps people in a group workspace. This concept is quite important in investigating the impacts of workspace characteristics on collaborative problem-solving tasks, because these characteristics may impact the ability to perform external cognition.

Gutwin and Greenberg [17] define awareness as the knowledge "created through interaction between an agent and its environment" (p. 5). They enumerate four fundamental aspects of awareness: i) awareness is about the state of the environment, ii) awareness needs to be maintained over time due to changes in the environment, iii) awareness maintenance is done through interaction with the environment, and iv) awareness is required to attain task goals and it is not the ultimate goal by itself.

There are many types of awareness discussed in the literature, see Schmidt [46] for an overview, but workspace awareness [17] is the most closely related to this research. Situation awareness is a more general concept, and because it is the basis of workspace awareness (WA), it is discussed first.

2.2.4.1 Situation Awareness

Several definitions of Situation Awareness (SA) have been developed, some domain-specific (e.g. aircraft piloting) and some more general. Perhaps the most common definition was given by Endsley et al. [9] as:

> "Situation awareness (SA) is the perception of environmental elements within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 36).

In a general sense, situation awareness means how you are aware of circumstances and events happening around you. As the definition of SA mentions, the time and space factors are emphasized [10] and [11]. Time is a significant factor for situation awareness, as it impacts how a person is aware of environment dynamics and data change rate [10]. As this thesis investigates the effects of table size on collaborative tasks, the second factor, space, is of special interest here. Endsley [11] reported that the spatial aspects of the domain directly impact perception of environmental elements and comprehension of their meaning, and can act as a stressor in case of limited space. In a table workspace, the limited space might have the same impact on browsing and external cognition.

An important aspect of SA in group and collaborative work is how individual and team awareness affect each other. Wellens [60] defined group situation awareness by connecting it to SA as "the sharing of a common perspective between two or more individuals regarding current environmental events, their meaning and projected future status" (p. 272). Endsley et al. [12] proposed a model for team SA containing team SA requirements, devices for collaborating and sharing information, mechanisms such as shared mental models, and processes for checking each other's information and coordination. While many researchers refer to team and group SA, it seems these concepts still need more work to take into account all the aspect of group dynamics.

Generally, awareness and design to support awareness are important issues in collaborative activities. In this context, it is important to understand how people continuously try to keep track of what is going on and of what the other people know or intend to do. Different types of awareness have been enumerated by focusing on various aspects of group work, such as peripheral awareness, background awareness, and workspace awareness, as discussed by Schmidt [46].

2.2.4.2 Workspace awareness

Gutwin and Greenberg [17] defined *workspace awareness* (WA) as "the up-to-the-moment understanding of another person's interaction with the shared workspace" (p. 3). They mentioned that WA is only related to awareness of what is happening inside the time and place boundaries of a collaborative task. They specified three main questions to 1) determine information considered by WA, 2) the way this information is collected, and 3) the way team members benefit from WA. For the first question, WA elements are described in three dimensions of who, what and where, in which "what" addresses human behavior and artifacts. According to Gutwin and Greenberg's viewpoint in the WA framework, external and physical artifacts are particularly important and their position, movement and direction can convey information to team members. These are mainly the factors studied in this thesis, and are tracked to investigate external cognition in a table workspace.

The third question in the WA framework deals with how WA is used by a team, which brings the collaboration factor to the picture. They mention three main ways WA is used by team members [17]: management of coupling (i.e., transitions between working independently and together), communication through visual evidence and gaze awareness, and coordination of actions. Dix et al. [8] defined a similar concept, feedthrough, as the mechanism of determining a person's interactions via the visual effects and sounds of artifacts. They stated that feedthrough is the way a user sees the effects of others' action in addition of feedback which is the way she observes the effects of his/her actions. Feedthrough provides "an additional channel of communication through the artefacts" [7] (p. 148), which Dix remarks as useful for specifically notify people what was happened in the workspace. If team members can see each other during taskwork, which is the case in the experiments in this thesis, feedthrough is combined with body movements and gestures (e.g. movements of hands and heads). For studies in this thesis it is important to consider how external cognition interacts with collaboration and how communication facilitates cognitive activities.

Tang et al. [57] also investigated different styles of collaborative coupling that is related to the WA. They concluded that coupling styles are linked to other parameters such as physical position (i.e. seating position). This is consistent with other research that shows a relationship between physical positions and individual/team activities of people around a table [51].

2.3 Chapter Summary

The main research theme of this thesis is the impact of physical workspace features on collaborative tabletop problem solving. Regarding this theme, this chapter briefly reviewed concepts in this domain and particularly covered issues related to the table workspace and associated taskwork. In the first part of the chapter the role of physical features in the workspace, especially the impact of table dimension on task activities was discussed. This review revealed that so far it has been only minimal research on the interaction between table physical features and collaborative tabletop problem-solving activities.

Table 1 shows the list of the physical features in a table workspace. The bold features are the ones studied in this thesis, and this chapter mainly focused on previous investigations related to these features. For table, the shape is assumed rectangular with a standard height and horizontal orientation. Features of artifacts are also under study and I assume rectangular artifacts for the studies, however of various sizes.

Table 1 - Physical Features of a Table Workspace

Entity	Features
Table	Shape: **<u>rectangular</u>**, round or customized shapes
	Dimensions: **<u>width</u>**, **<u>length</u>** and height
	Surface orientation: **<u>horizontal</u>**, angled or vertical
Artifact	Shape: **<u>rectangular</u>** or custom shapes (e.g. puzzle pieces)
	Dimensions (i.e., size)
	Number of artifacts

For task activities, this chapter addressed external cognition, visual search and awareness (especially workspace awareness). These concepts are essential in investigating significant factors in tabletop collaboration. External cognition is a key concept, because it is directly related to the benefits of providing physical space on a table workspace to assist cognition and collaboration. Workspace awareness is essentially the combination of external cognition with teamwork, and this type of awareness plays a key role in considering collaboration in the thesis studies. Workspace awareness especially helps study how participants work individually and collaboratively in a table workspace.

Chapter 3
Observational Study: Collaborative problem-solving activities on traditional tables

An observational study in a laboratory setting was conducted to understand how tabletop size impacts external cognition during open-ended problem solving tasks involving traditional, paper-based media. This chapter details the study methodology including, participants, task types, experimental design, and procedures of the study. Additionally, data collection and analysis techniques will be discussed.

3.1 Participants and Setting

Thirty-two University of Waterloo students (18 male and 14 female), all paid volunteers, participated in the study. The students, ranging in age from 20 to 30 years old, were recruited (See Appendix A) from a variety of academic backgrounds, including Science, Engineering, and Humanities. Participants completed the study in pairs, half of the pairs were self-selected, i.e., they volunteered together, while the remaining pairs consisted of individual volunteers matched by the experimenter based on schedule availability.

The study was conducted in a laboratory setting. In each study trial, one of two tables was placed in the center of the room: a small table (77cm x 124cm, 146cm diagonal) or a large table (154.5cm x 124cm, 198cm diagonal).

In this study, two seating arrangements were included. As shown in Figure 1, participants either sat across the table from one another (across seating arrangement with 124cm between them), or along adjacent sides of the table at right angles to one another (corner seating arrangement). Participants were permitted to stand up and to move only along their side of the table.

A video camera was placed in the room to capture tabletop interactions, and clip-on lavaliere microphones were used to capture participants' conversations. The experimenter recorded Field notes during each study trial.

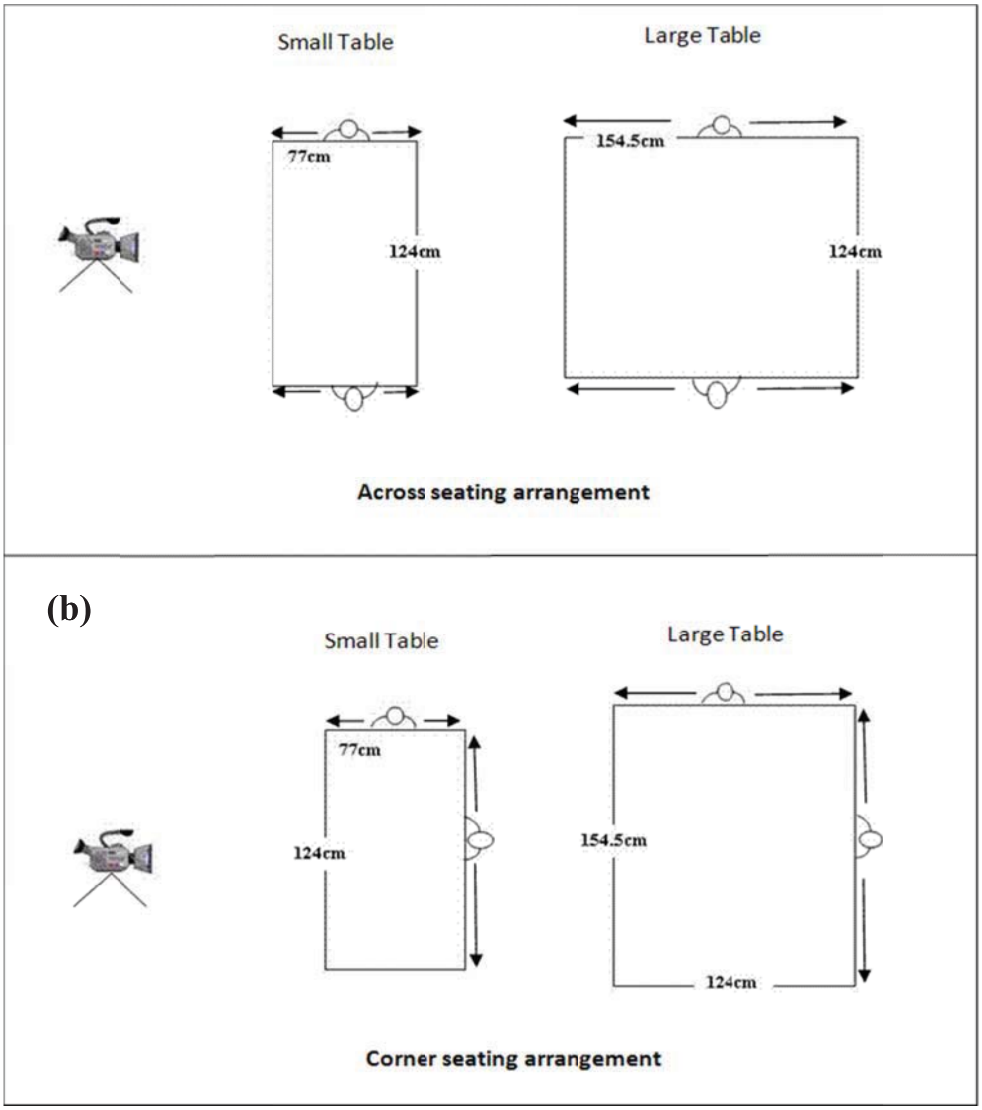

Figure 1: The two seating arrangements on each table size.

3.2 Experimental Design

The study used a 2 (table size) x 2 (task) x 2 (seating arrangement) mixed design, in which all pairs of participants experienced both table sizes and tasks, but only one seating arrangement. Task and table size were independent variables, while pairs and seating arrangement were each an independent variable between pairs (See Appendix C).

3.3 Experimental Tasks

Participants performed two problem-solving tasks on each of the large and small tables: story-telling and travel-planning. These types of creative problem-solving tasks are often used in tabletop collaboration studies [19][36][48]. The design of the story-telling and travel-planning tasks was refined during pilot studies. A detailed description of each task follows.

Story telling: Pairs were asked to create a story using photos from a well-known American television series (Seinfeld or Friends). Instruction sheets (found in Appendix B) were provided containing five possible themes upon which participants could base their story; however, use of these themes was not mandatory. Task materials included a black storyboard (45cm x 45cm), upon which pairs could build their story. The use of storyboard allowed participants to easily reorient or reposition the story line on the table. It also provided more clear distinction of when participants were working on the story solution versus simply getting familiar with the study materials. Materials also included a set of 56 photos (9cm x 9cm) consisting of various scenes from show episodes printed on thick, card-stock paper. Both the large and small tables were sufficiently large to accommodate all task materials without overlap (see Figure 2 (a) and (b)).

Travel planning: Instruction sheets were (found in Appendix B) provided for pairs and they were asked to create a three-day, two-night itinerary for a family of four visiting a Canadian city (Calgary or Vancouver), with a specific budget. Near the end of the task, pairs were informed of a new problem constraint: a grandmother in a wheel chair (for the Calgary destination), or two young cousins (for the Vancouver destination) would join the family on the second day. Thus, the itinerary had to be modified to accommodate the additional traveler(s). Pairs were provided with 27 information sheets, 10 small (12.5cm x 13.5cm), 16 medium (21cm x 21cm), and 1 large (28cm x 22cm) sheets with attractions, maps, and driving distances printed on thick, card-stock paper. Blank paper and pen were also provided for recording the itinerary. Significant overlap occurred when materials were spread out on the small table (Figure 2 (c)); however all materials could be accommodated without overlapping on the large table (Figure 2 (d)).

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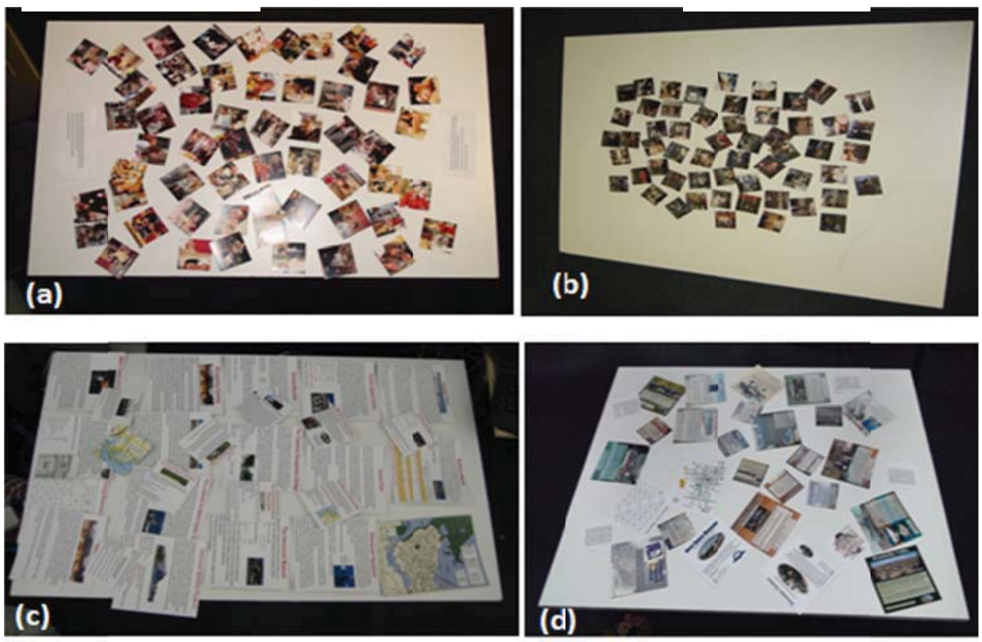


Figure 2: (a) Story-telling materials on the small table, (b) Story-telling materials on the large table (a) Travel-planning materials on the small table, (d) Travel-planning materials on the large table

3.4 Procedure and Data Collection

Each study trial was structured as follows. Pairs were welcomed, seated according to their assigned seating positions, and asked to read information sheet (see Appendix D) and to complete a consent form (Appendix E). They then completed four experimental trials. In each trial, the experimenter explained the task and any questions were answered. In their first two trials, pairs completed the travel-planning or story-telling task on both table sizes. The order of presentation of task type and table size was counter-balanced across pairs. In the second two trials, pairs completed the remaining task, again on both tables, with the order of table size held constant from the first two trials. Ordering of task scenarios (i.e., city destination for travel-planning and television series for story-telling) remained constant across pairs. The trial ordering for each pair is provided in Appendix C-Experimental Design.

Pairs were given approximately 20 minutes to complete each trial; however, more time (3-5 minutes) was typically given for the travel-planning task, as pairs had difficulties finishing their itinerary in the allotted time. After completing the four trials, pairs participated in a post-experiment interview with the experimenter. The interview explored participants' space usage strategies and their satisfaction with the task processes and outcomes. Participants were then verbally debriefed, provided with a feedback letter (see Appendix F-Thank you letter for participants), thanked, and compensated with $10 (for each participant) for their involvement.

3.5 Data Analysis

An in-depth video data analysis was performed on the collected data. The goal of the data analysis was to extract quantitative and qualitative behaviors relevant to external cognition and to understand how these behaviors were influenced by independent variables of the study, table size, task type and seating arrangement. The following subsections describe the data coding schema provided for extracting these behaviors and will show how the coded data was used for qualitative and quantitative analysis.

3.5.1 Data Coding

The first step of the video analysis was to establish a coding scheme. The open coding method was used [54] in order to ground the data analysis in the collected data. This method involves the iterative development of a coding schema, which becomes more refined and focused through in-depth data exploration. For this purpose, field notes were first reviewed to identify overall patterns and factors anticipated to be related to external cognition during joint and individual activities on the table. The initial coding scheme was also influenced by related work on problem-solving and external cognition [31] [45] (See Appendix G[5] for details of the initial coding schema).

On review and after initial coding passes of the video data, it was found that the initial coding scheme did not capture all data relevant to external cognition. As a result, additional behaviors were identified from video and field notes, and the coding scheme was extended to capture these behaviors. The coding schema highlights the use of external cognition by pairs on the table, and allows a characterization of the qualitative behaviors relevant to external cognition.

The final coding scheme is presented in the first column of Table 2. The second column of the table presents the aspects of coded data from the first column that was counted for quantitative analysis. The third column of Table 2 presents the aspect of the coded data from the first column that was captured for qualitative analysis.

[5] Appendix G is available in the enclosed CD

Table 2- Data Coding Schema

	Coding scheme	What was measured for quantitative analysis?	What kinds of questions were answered for qualitative analysis?
Above-the-Table	**Materials Usage**	Number of times that materials were used above-the-table	What, if anything hindered the use of the available space on the table? Why were materials used above the table?
On-the-Table	**Spatial Usage**	Percentage of the table usage	How did they use different parts of the table? Why did they not use some parts of the table?
	Task Process • Problem understanding • General organization • Possible candidate • Discard item • Sub-solution of the problem • Solution making	Number of times that the table was used for these purposes	For what purposes did they use external cognition?
	External Cognition • Cognitive tracing • Grouping o Intra-group pilling o Visual Separation ▪ Inter-group visual separation ▪ Intra-group visual separation ▪ Inter-group and Intra-group collapse	Number of times that cognitive tracing and grouping occurred on the table	What prompted participants to use different kinds of external cognition? What, if anything, hindered the use of external cognition?
	External Cognition effects • Workspace awareness • Parallel search • Serial search	Number of times that glancing, scanning, fixating happened on materials on the table	What kinds of external cognition led to each of these events?

Above-the-table and on-the-table usage of the space were each coded separately, as it is possible for participants to hold materials above the table. Also as the goal of this research is to ultimately apply its results to the design of digital tabletop displays, the distinction between what is done on or above the table is important as many tabletop interfaces only provide a two dimensional plane for users to interact with media, which would be more closely emulated by the on-the- table interactions.

Due to time constraints, in-depth video coding was only conducted for eight of the sixteen total pairs, such that one of each possible eight combinations of study conditions (task x table x arrangement) was coded (see Appendix G for full details of coded data). The following sections will describe the coding scheme from Table 2 more detail.

3.5.1.1 Above-the-table – Material usage

As shown in Figure 3, sometimes participants used the area of above-the-table for doing part of their activity, for example, due to space limitations or to get a closer look at the materials. In each trial, the number of task materials that were held above the surface was counted during the task. This number included both materials that were used to complete the task and materials that were simply held (and not used), for example, to compensate for space constraints. Figure 3 shows two events which pairs are working above-the-table.

Figure 3: Above the table activities

3.5.1.2 On-the-table – Spatial usage

To understand how groups each used the available space on the table in each trial, snapshots were collected from the whole video streams showing areas of the table that participants never used. Analysis of all snapshots from a particular trial determined the areas of the table that were never used across the whole trial. As shown in Figure 4, the unused areas (across the whole trial) are highlighted in red in the snapshots. A perspective grid was overlaid onto the snapshot to determine the percentage of used and unused (red highlighted area) area on the table. The snapshots for each trial are provided in Appendix H-Spatial usage.

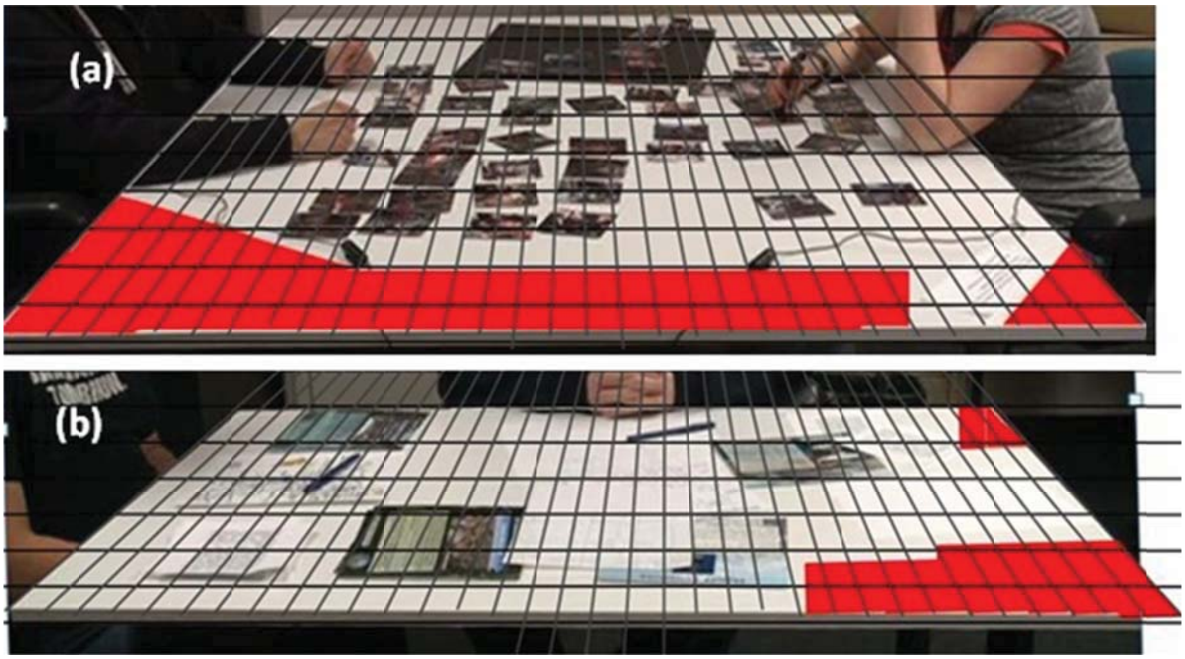


Figure 4: (a) The perspective grid overlaid on the large table, (b) The perspective grid overlaid on the small table (Red highlighting indicates unused areas of the table across the whole trial)

As the focus of this research is to understand how people work on the surface of different size of tables in order to design of digital tabletops, the subset of "on-the-table" was coded further.

3.5.1.3 On-the-table - Task process

Upon reviewing the data it appeared that all groups sessions could be broken down in six phases of task processing *on the table*, which were also consistent with ones in the sensemaking literature (e.g., [1]).

Problem understanding: Problem understanding events describe period of time when participants were looking, scanning, and searching the task material on the table. Typically, pairs investigated their problems in three steps:

1. General understanding of the problem and available task material
2. Understanding materials for creating a solution (i.e. solution making)
3. Understanding materials for problem refinement

General understanding refers to times that participants were scanning instructions and information sheets to find out what kind of problem they had to solve and what kind of materials were available for solving that problem. *Understanding for solution making* refers to times when participants were looking and reading through the available materials for candidates to solve the problem. After creating a solution, some pairs engaged in *understanding* materials *for problem refinement*, which was when participants were searching through materials not used in their solution to find more (or alternative) task materials to improve their solution.

General organization: general organization events occurred when participants physically put materials in different places on the table for the purpose of investigating, selecting, discarding, creating territories, or building the solution. Figure 5 illustrates two examples of general organization: (a) illustrates participants putting task materials in a shared space in the middle of the table (i.e., in a group territory) for joint activity, and (b) illustrates participants putting task materials at the sides of the table (i.e., in personal territories) for individual activity.

Figure 5: (a) Materials in the middle for joint understanding, (b) Information sheets in personal area for individual understanding

Possible candidate(s): A possible candidate event was coded when participants selected potential task materials for including in the story or in the travel plan. Figure 6 shows a pair selecting possible candidate materials on the shared part of the table.

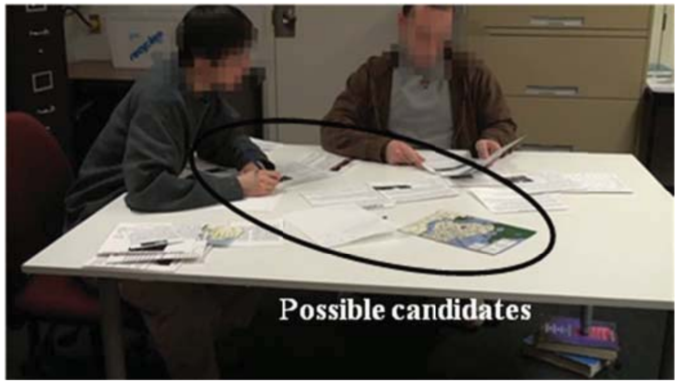


Figure 6: Selected task materials from information sheets pile during a travel planning trial.

Discard item: In each trial, the action of putting away one or more task objects and not using it/them, either temporarily or permanently, was coded as a discard item. Usually, pairs put discarded material(s) at a peripheral location, such as along the table edge. Some pairs simply turned over discarded materials or verbally indicated that the material was no longer being considered. In Figure 7, the pair placed discarded materials at the far end of the table.

Figure 7: Discarded task materials at the far end of the table during a travel planning trial

Sub-solution(s): Sub-solution events occurred when participants made different scenarios for the story or itinerary with only a few photo cards or information sheets. Pairs combined some or all of these scenarios together to complete a full story or itinerary.

Solution making: The process of putting together the final solution was coded as a solution-making event. *In story-telling*, actions of ordering, reordering, adding and removing the photo cards were coded as solution making. Solution making events also occurred whenever participants described the current story sequence on the table, because this activity was a form of solution evaluation, where the group assessed whether the story needed further improvement. In *travel planning*, the clear indicator of action for solution making was writing the plan on paper. Usually, before writing the plan, participants talked about different parts of the plan while making reference to the related card. Sometimes they ordered information sheets chronologically on the table to show each day plan. Either of these two kinds of actions was also coded as solution making event.

3.5.1.4 On-the-table - External cognition

To understand how participants interacted with information through the use of task materials (external representations) and how they modified and structured them *on the table* for their cognition, different kinds of external cognition behaviors were coded. Participants engaged in these behaviors by manipulating task materials *on the table* in order to support cognition at different stages of collaborative activities.

External cognition started at the beginning of the task as participants repositioned materials from the primary pile located at center the table. External cognition continued when participants distributed task materials, piled them, or separated one or pair(s) of task materials from others on the table to help better organize and understand the task and the possible solutions.

Cognitive tracing: Cognitive tracing was the main external cognition behavior involved in the task process. In the story-telling task, pairs had to have a sequence of pictures on the table. To accomplish this, pairs ordered, reordered, inserted, and removed photo cards, all of which were coded as cognitive tracing (and solution making as described earlier). However, in the travel-planning task, participants were asked only to write the itinerary on paper. Some pairs put the related information sheets beside each other in a chronological order to optimize the position of task materials in the proposed plan. In such cases, the process of ordering cards was coded as cognitive tracing for solution making (see Figure 8 and Figure 9).

Figure 8: Cognitive tracing toward solution making in story-telling.

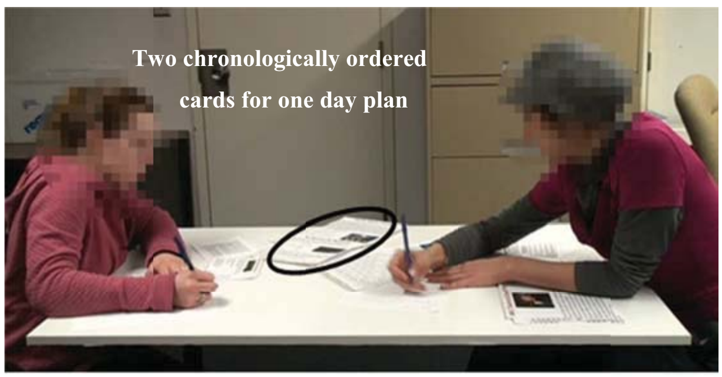


Figure 9: Cognitive tracing toward solution making in travel planning.

Grouping: When participants implicitly or explicitly categorized materials on the table, a grouping event was coded. Sometimes participants explicitly paired task materials by similarity or by intended use in their solution and sometimes they did not explicitly pair materials, instead putting a pair of task materials in the same area or in a pile without any verbal signal. For example, in the story-telling trials when a participant was looking at pictures and putting them on the table one by one (separately or in a pile), this situation was coded as grouping (grouped as *previously examined materials).* Figure 10 shows examples of grouping used in a pair. To distinguish separated materials from piled material, the sub-codes of grouping events were also used: *Intra-group pilling* and *visual separation* materials were coded.

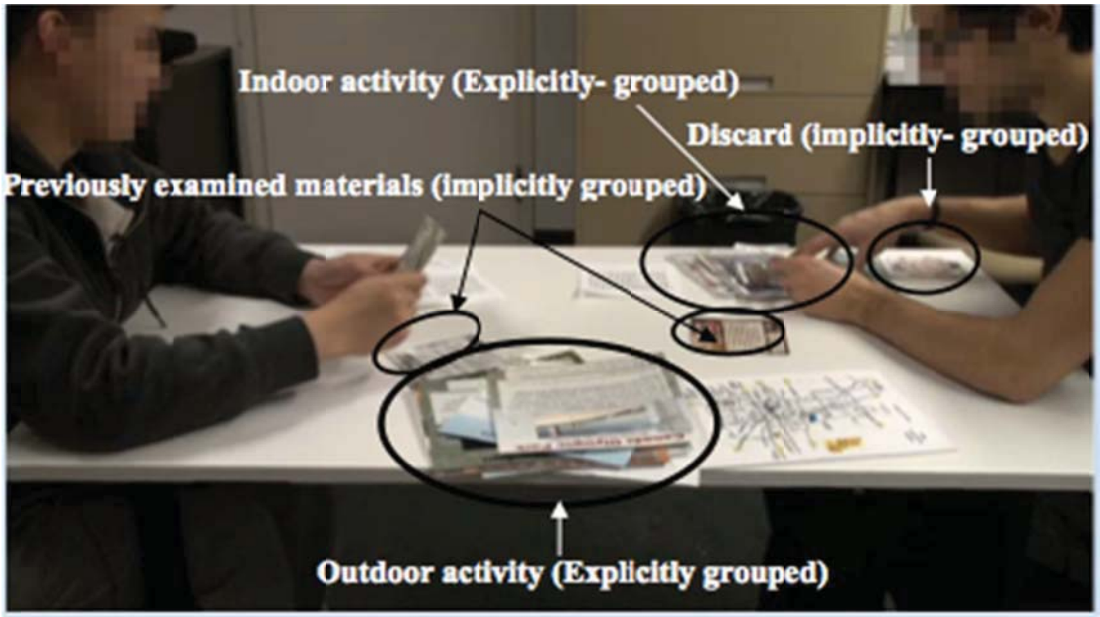


Figure 10: Piles of grouped materials

Visual separation: Some groups spread out materials on the table for the purpose of looking at more than one item at once or for pairing similar task materials in the same area. The act of expansion and distribution of task material on the table was coded as a visual separation event. Figure 11 shows examples of visual separation during travel planning and storytelling.

Figure 11: Visual Separation

If the distribution of task materials on the table belonged to the same group of task materials, visual separation was coded as *intra-group visual separation*. If materials from different groups were expanded on the table, visual separation was coded as *inter-group visual separation*. For example in Figure 12, the participants are placing story-telling photos such that each photo can be seen while maintaining spatial separation between groups of similar photos. In this snapshot, each circle was coded as intra-group separation. Participants in Figure 12 also have visual separation of three categories of photos, which was coded as inter-group visual separation. They visually separated materials of one group, intra-group visual separation, and by little space between different categories of pictures they made four different groups of pictures, inter-group visual separation.

Figure 12: Intra-group visual separation

If participants eliminated the distribution of task materials on the table, depending on the type of distribution, *intra-group collapse* or *inter-group collapse* was coded.

3.5.1.5 On-the-table - Effects of external cognition

Based on reviewing the data and initial video coding, several effects of external cognition emerged, and were including in the coding schema:

- Workspace awareness
- Parallel search
- Serial search

Workspace awareness: When a participant was observed glancing at, scanning or fixating on their partner's materials or his/her actions on the table, a workspace awareness event was coded. This code captured when participants in a pair observed what their partner was doing on the table, which material he/she was working with and how external cognition of the partner was supporting their workspace awareness [17].

The participant at the right of Figure 13 is describing the story by sequentially pointing to the ordered photo cards. Her partner is looking at the story line and the result of her activity (what she did), helping him to understand that she is investigating their final solution (i.e., what she is doing).

Figure 13: Workspace awareness provided by external representations

Parallel search: occurrences of participants looking at multiple items at once (enabled by visual separation on the table) were coded as parallel search. Participants in Figure 14 are performing parallel search of task materials. This picture shows a pair using the opportunity of having all information sheets visually available through visual separation on the table for parallel search.

Figure 14: Distribution of materials on the table and visual search

Serial search: When participants were looking at task materials one by one from a pile, serial search was coded. As shown in Figure 15, the participant on the right is performing a serial search by leafing through information sheets from a pile on the table (The left side participant is doing the same thing but *above the table* which is not coded.)

Figure 15: Serial search by leafing through task material

3.5.2 Qualitative and Quantitative Data Analyses

A quantitative analysis was done on captured counts of events from the quantitative data, see Appendix G for coding tables, extracted from the coded data. Repeated measure analysis of variance (RM ANOVA) was applied to the data to determine whether table size affected the number of times that external cognition and its associated behaviors (see Table 2, first column) occurred during the study. RM ANOVA was also conducted to test whether other study factors, i.e. task type and seating configuration significantly influenced external cognition behavior. The detailed results of the quantitative analysis are presented in Chapter 4.

The qualitative analysis aimed to gather an in-depth understanding of the effects of the study factors on pairs' behaviors and the reason(s) for the observed behaviors. After several reviews of the video data, affinity diagrams [27] were created using snapshots and notes captured from videos of each trial of the study. This process involved clustering and grouping related events to describe behavioral themes. The results of the qualitative analysis are presented in Chapter 5.

3.6 Chapter summary

This chapter presented the methodological details of an observational study that investigated traditional tabletop activities. Design factors of the study, the procedure of the study, and data analysis were described. The video coding process described in this chapter sheds light on the external cognition and its influencers with the specific goal of determining the effect of table size, and the other study factors, on external cognition. To understand if these study factors influenced participants' external cognition behavior during tabletop activities, quantitative and qualitative data analyses were conducted and the results will be discussed in next the two chapters.

Chapter 4
Quantitative Data Analysis

A significant amount of quantitative data was collected during the coding process described in chapter 3. Quantitative analysis specifically was done to understand whether the independent variables, table size, task type and /or seating arrangement have a statistically significant effect on the user behaviors. The following sections illustrate the results of quantitative analysis of data extracted from the coding scheme (see Appendix G)[6].

When reporting results the standard significance level used in HCI research was adopted, specifically seeking 95% confidence levels. However, because of the limited sample size and the ambiguous nature of the behaviors being coded, statistical trends also are highlighted, i.e. confidence values between 90-95%.

4.1 Initial coded events

As described in the Chapter 2, standard measures of external cognition (Cognitive tracing and grouping) [52] and problem-solving processes (Problem understanding, developing, carrying out and evaluation the plan) [31] were identified from relevant research literature to develop the coding scheme. In addition to these measures, above-the-table material usage and spatial usage of the table were also included in the initial coding scheme. Quantitative analysis was done on external cognition behaviors, above-the-table material usage and spatial usage of the table measures to determine the influence of the independent variables on these events. The following subsections show the results of quantitative analysis from the initial coding scheme.

4.1.1 Above-the-table material use

On digital tabletops users cannot examine digital versions of materials above the table, so the design of a digital table must address this deficiency, using interactive techniques that compensate for the fixed viewing plane. In this section, above-the-table content manipulations, such as Figure 16 will be analyzed to understand the factor(s) that caused pairs to manipulate information above the surface of the table and the frequency with which in-air manipulations occur.

[6] Appendix G is available in the soft copy, for the sake of brevity

Figure 16: instances of material usage above the table

The number of times that each pair manipulated materials above the table in each trial was counted and is shown in Table 3.

Table 3- Above-the-table materials use

Above-the-Table materials		**Small Table**		**Large Table**	
		Story-Telling	**Travel-Planning**	**Story-Telling**	**Travel- Planning**
Position	**Pair**				
Across	**G2**	850	511	271	196
Across	**G6**	638	366	172	361
Across	**G7**	484	305	608	309
Across	**G14**	1551	435	469	256
Corner	**G10**	2023	932	1890	404
Corner	**G11**	1903	529	826	441
Corner	**G12**	438	517	732	293
Corner	**G16**	1047	1261	890	323

A repeated measure analysis of variance (RM ANOVA) test was done to compare the occurrence of above- the- table materials' use function of the table size and task condition. A QQ-plot shows that the original data does not have normal distribution. Shapiro-Wilk test also gives a test statistic of 0.931 and a P-value of 0.0427. Therefore, the hypothesis of having normal errors is rejected. By applying logarithmic transformation[7] to the data set, the distribution becomes roughly normal. Shapiro-Wilk test endorses the QQ-plot result, yielding a test statistic of 0.972 and p-value of 0.5547.

[7] Natural logarithmic function

Statistical analysis on the transformed data showed that a significant difference exists in the number of above-the-table material usage events between table sizes (F =12.35, D of freedom= 1, P=0.0126) with more above the table material usage occurring on the small table condition (in logarithmic scale – Small table: mean=6.59, Std Dev=0.6, Large table: mean =6.06, Std Dev=0.63).

No interaction effect was found, but a significant difference was found in the number of above-the-table material usage events between task types (F=16.66, D of freedom= 1, P=0.0065) with more in the travel-planning task (in logarithmic scale - Story-telling: mean=6.62, Std Dev=0.7 – Travel-planning: mean =6.03, Std Dev= 0.47).

A one-way ANOVA was conducted to compare above-the-table material usage across seating arrangements. A significant difference was found (F=9.12 – P Value=0.02). Participants exhibited more above-the-table material usage in the corner seating arrangement (Across: mean=6.03, Std Dev=0.56 – Corner: mean=6.62, Std Dev=0.63).

The statistical tests on the number of above- the- table material usage events reveal that table size, task type and seating arrangement have significant effect on above- the- table interaction.

4.1.2 Spatial usage of the tables

To determine if usage of space was increased on the large table, the amount of table space use was counted based on the technique described in Section 3.5.1.2.

A repeated measure analysis of variance (ANOVA) test was done to compare the spatial usage, across table size and task condition. QQ-plot shows that the original data has a normal distribution, and Shapiro-Wilk test also confirms this with a p-value of 0.4960.

A significant difference was found in the incidence of spatial usage between table sizes (F =443.53, Error D of freedom= 1, P <.0001). The participants had more spatial usage on the large table (Small table: mean=8876.6 cm^2.54, Std Dev=709.1 – Large table: mean=14811.19 cm^2, Std Dev = 2096.7).

Table 4: Spatial usage

Spatial usage		Small Table		Large Table	
		Story- Telling	Travel- Planning	Story-Telling	Travel- Planning
Position	**Pair**				
Across	**G2**	8944.64	9157.65	15772.15	15297.03
Across	**G6**	9271.76	9015.96	15207.36	16535.38
Across	**G7**	8857.15	8796.29	15730.17	17808.06
Across	**G14**	9411.55	9242.28	15012.73	17935.9
Corner	**G10**	6458.85	8414.96	11345.41	14106.4
Corner	**G11**	9209	9509.5	11398.84	14215.16
Corner	**G12**	9143.38	9226.12	12799.37	16581.17
Corner	**G16**	8589.93	8776.31	11683.14	15550.81

No interaction effect was found between size and task, but a significant difference was found in the spatial usage between task types (F =53.47, Error D of freedom= 1, P=0.0003) with more spatial usage in the travel-planning task (Story-Telling: mean=11177.2 cm^2, Std Dev= 2942.2 – Travel-Planning: mean =12510.6 cm^2, Std Dev=3752.1).

A one-way ANOVA was conducted to compare cognitive tracing across seating arrangements. A significant difference was found (F = 14.89, Error D of freedom= 1, P= 0.0084). Participants exhibit more spatial usage when sitting in the across arrangement (Across: mean=12624.8 cm^2, Std Dev=3740.6 cm^2 – Corner: mean=11063 cm^2, Std Dev=2896.5).

As the results show, all independent variables in the study had effects on space utilization on the table. Figure 17 is one example that shows how large table size increases usage of the space on the large table for one type of task.

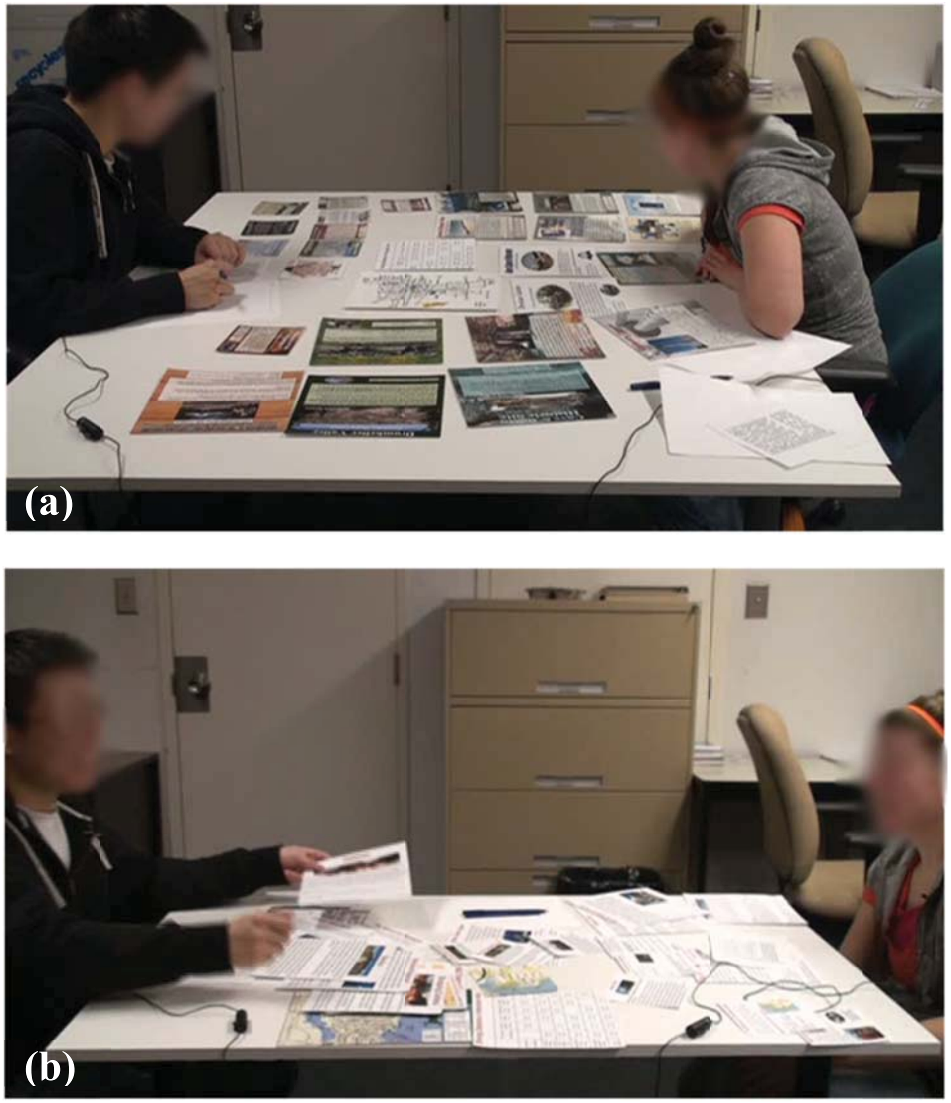


Figure 17: Travel-Planning task on small and large tables in across seating arrangement
In picture (a) participants used 51.88% more space than in picture (b)

4.1.3 On- the table, external cognition measures

Analysis was done on data related to two types of external cognition measuring, cognitive tracing and grouping (visual separation and piling) to understand what caused changes in these behaviors over different study configurations.

4.1.3.1 On- the table, Cognitive Tracing measures

In this section, cognitive tracing events are analyzed to reveal the factor(s) that caused participants to manipulate materials enabling cognitive tracing on the table. Ordering, reordering, inserting and removing materials both for the purpose of solution making and evaluating a solution were coded as cognitive tracing events see Figure 18.

Figure 18: (a) Cognitive tracing on ordered information sheets (b) Cognitive tracing on ordered photos

The frequency with which cognitive tracing occurred is shown in Table 5.

Table 5: Cognitive Tracing measures

Cognitive Tracing		Small Table		Large Table	
		Story-Telling	Travel- Planning	Story-Selling	Travel-Planning
Position	**Pair**				
Across	**G2**	20	2	29	6
Across	**G6**	34	1	35	34
Across	**G 7**	32	12	37	3
Across	**G14**	22	2	25	15
Corner	**G10**	27	5	28	15
Corner	**G11**	49	18	43	24
Corner	**G12**	38	3	26	15
Corner	**G16**	33	3	50	3

A repeated measure ANOVA test was conducted to compare the occurrence of cognitive tracing across table size and task type. A QQ-plot shows that the original data has a normal distribution, and Shapiro-Wilk test also confirms this with a p-value of 0.2796.

A significant difference was found in the number of cognitive tracing events between table sizes (F=6.03, Error D of freedom= 6, P=0.0494). The participants performed more cognitive tracing on the large table (Small table: mean=18.81, Std Dev=15.46 – Large table: mean=24.25, Std Dev = 13.96).

No interaction effect was found between size and task, but a significant difference was found in the number of cognitive tracing events between task types (F=78.51, Error D of freedom= 6, P=0.0001), with more in the story-telling task (Story-Telling: mean=33, Std Dev= 8.84 – Travel-Planning: mean =10.06, Std Dev=9.53).

A one-way ANOVA was conducted to compare cognitive tracing across seating arrangements. No significant difference was found. (F= 1.09, Error D of freedom= 6, P= 0.3370). (Across: mean=19.31, Std Dev=13.50 – Corner: mean=23.75, Std Dev=16.02).

The results above show that table size and task type had significant effects on frequency of cognitive tracing in the study; however the seating arrangement did not have any significant statistical effect.

4.1.3.2 On- the table, Piling Measures

Whenever participants in the study added an item to a stack of materials on the table for categorizing, selecting and discarding, a piling event was coded (see Figure 19). Incidents of piling events were measured and shown in Table 6.

Figure 19: Piling events

Table 6: Piling measures

Piling		Small Table		Large Table	
		Story- Telling	Travel- Planning	Story- Selling	Travel -Planning
Position	**Pair**				
Across	**G2**	36	35	12	22
Across	**G6**	17	57	2	36
Across	**G 7**	4	36	4	6
Across	**G 14**	17	36	7	8
Corner	**G 10**	17	18	24	7
Corner	**G 11**	21	21	7	14
Corner	**G 12**	15	47	11	13
Corner	**G 16**	11	41	18	33

A repeated measure ANOVA test was conducted to compare the occurrence of piling across table size and task type. QQ-plot shows that the original data has a normal distribution, and the Shapiro-Wilk test also confirms this with a p-value of 0.0606.

A significant difference was found in the number of piling events between table sizes (F=34.38, Error D of freedom= 6, P=0.0011). Participants performed more piling on the small table (Small table: mean=26.81, Std Dev=14.57 – Large table: mean=14, Std Dev = 10.10).

No interaction effect was found between size and task, but a significant difference was found in the number of piling events between task types (F=6.86, Error D of freedom= 6, P=0.0396) with more in the travel-planning task (Story-Telling: mean=13.94, Std Dev= 8.72 – Travel-Planning: mean =26.88, Std Dev=15.38).

A one-way ANOVA was conducted to compare piling across seating arrangements. No significant difference was found. (F= 0.06, Error D of freedom= 6, P= 0.8165). (Across: mean=20.94, Std Dev=16.40 – Corner: mean=19.88, Std Dev=11.5).

The result of quantitative analysis show that table size and task type has significant effect on piling events, but seating arrangement did not have any significant statistical effect.

4.1.3.3 On- the table, Visual separation measures

When material was separated from other material or pile(s) of material, intra and inter-group visual separation materials was coded, see Figure 20.

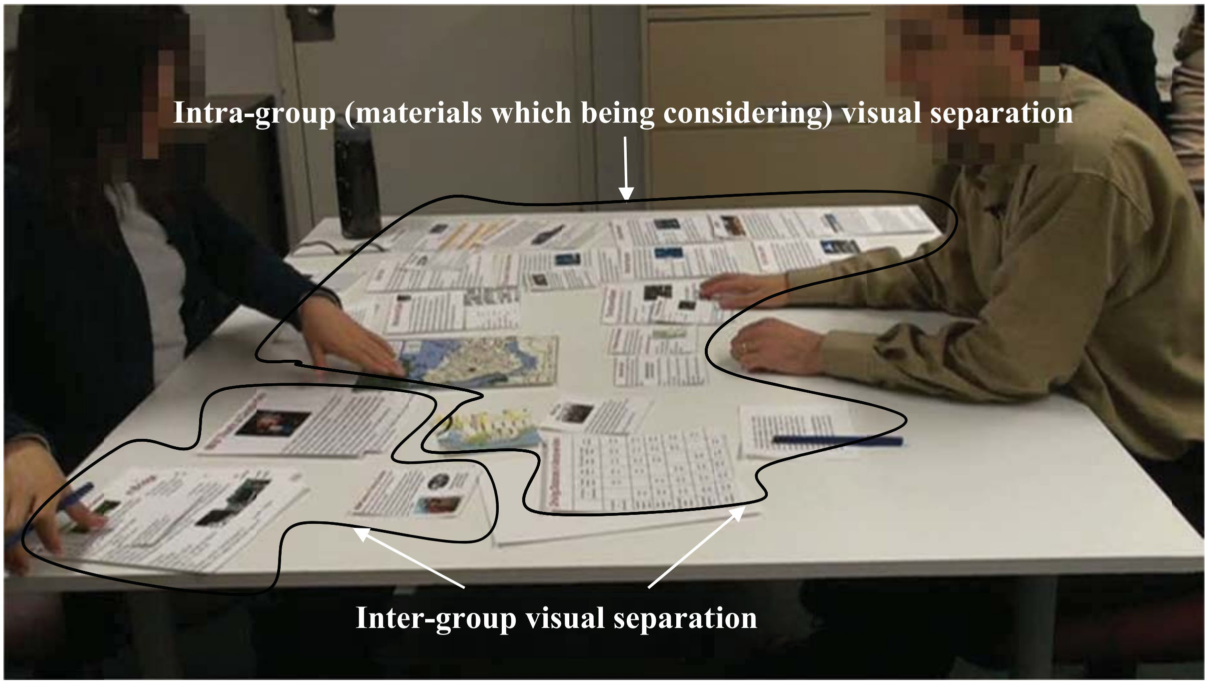


Figure 20: Intra and inter-group visual separation events

Incidents of visual separation events were measured and shown in Table 7. A repeated measure ANOVA test was conducted to compare the occurrence of visual separation across table size and task type. A QQ-plot shows that the original data has a normal distribution, and the Shapiro-Wilk test also confirms this with a p-value of 0.1428.

A significant difference was found in the amount of visual separation between table sizes (F=9.94, Error D of freedom= 6, P=0.0198). The participants had more visual separation on the large table (Small table: mean=37.19, Std Dev=13.62 – Large table: mean=44.81, Std Dev = 13.48).

No interaction effect was found between size and task, but a significant difference was found in visual separation between task types (F=14.07, Error D of freedom= 6, P=0.0097) with more in the story-telling task (Story-Telling: mean=48.38, Std Dev= 12.31– Travel-Planning: mean =33.63, Std Dev=11.42).

Table 7: Visual separation measures

Visual Separation		Small Table		Large Table	
		Story- Telling	Travel- planning	Story- Telling	Travel-Planning
Position	**Pair**				
Across	**G2**	39	18	50	27
Across	**G6**	56	38	39	50
Across	**G 7**	43	33	54	29
Across	**G 14**	71	27	77	40
Corner	**G 10**	33	17	34	38
Corner	**G 11**	56	31	49	64
Corner	**G 12**	41	32	44	32
Corner	**G 16**	40	27	48	35

A one-way ANOVA was conducted to compare visual separation across seating arrangements. No significant difference was found. (F= 0.54, Error D of freedom= 6, P= 0.4886). (Across: mean=43.19, Std Dev=12.31 – Corner: mean=38.81, Std Dev=11.53).

The quantitative analysis results show that table size and task type both had significant effect on number of visual separation events observed during the study, but seating arrangement did not.

4.2 Extended coded events

A strong effect of table size on external cognition behaviors was found in the previous section. As noted in chapter 3, by revisiting the analysis of initial codes, additional behaviors attached to external cognition were identified and the initial coding scheme was extended. Workspace awareness, parallel search, and serial search were identified as behaviors of interest for external cognition. The goal of this section is to determine if these additional behaviors are influenced by table size, seating arrangement and task type.

4.2.1 Work space awareness

When a participant saw what his/her partner was doing on the table by looking at the partner's manipulations or looking at task material the partner had previously manipulated, a workspace awareness event was coded (See Figure 21).

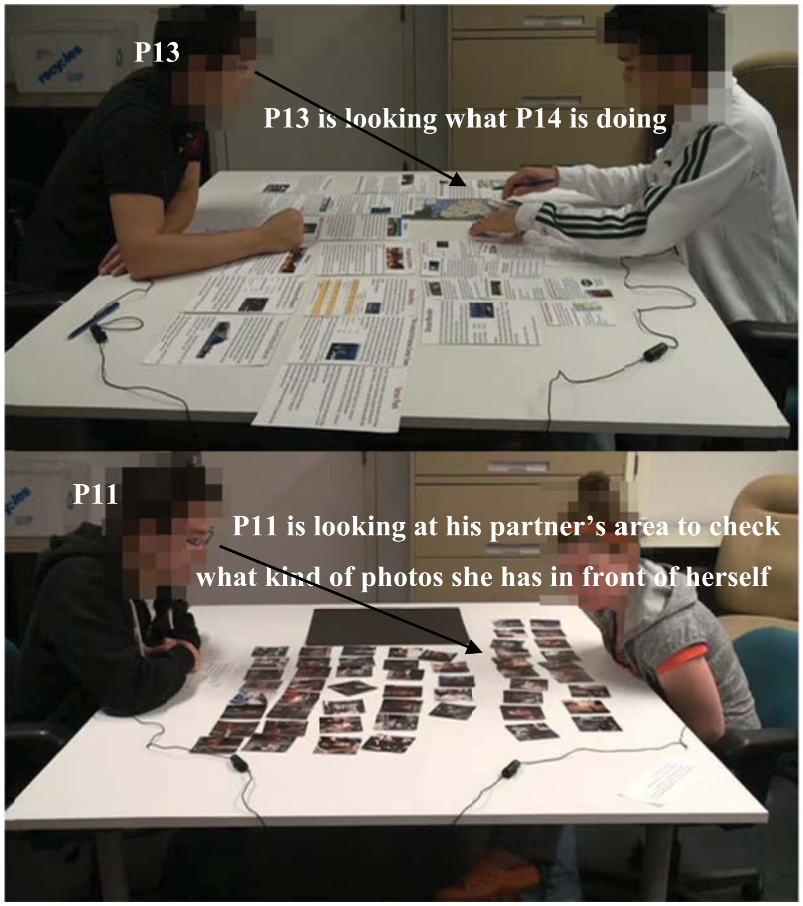


Figure 21: Workspace awareness

Incidents of workspace awareness events were measured and are shown in

Table 8. A repeated measure ANOVA test was done to compare the workspace awareness across table size and task conditions. A QQ-plot shows that the original data has a normal distribution, and the Shapiro-Wilk test also confirms this with a p-value of 0.1943.

No significant difference was found in the number of workspace awareness events between table sizes (F=2.45, Error D of freedom= 6, P=0.1686). (Small table: mean=74.25, Std Dev=30.8 – Large table: mean=80.25, Std Dev =24.15).

No interaction effect was found between table size and task, but a significant difference was found in the number of workspace awareness between task types (F=10.29, Error D of freedom= 6, P=0.0184) with more incidents of workspace awareness in the travel-planning task (Story-Telling: mean=66.88, Std Dev= 22.59– Travel-Planning: mean =87.63, Std Dev=28.48).

Table 8: Workspace awareness

Awareness		Small Table		Large Table	
		Story- Telling	Travel -Planning	Story-Telling	Travel- Planning
Position	**Pair**				
Across	**G2**	47	57	53	58
Across	**G6**	67	78	59	123
Across	**G 7**	48	42	45	74
Across	**G 14**	88	150	92	123
Corner	**G 10**	40	97	84	77
Corner	**G 11**	106	111	109	98
Corner	**G 12**	70	61	63	84
Corner	**G 16**	41	85	58	84

A one-way ANOVA was conducted to compare workspace awareness across seating arrangements. No significant difference was found. (F= 0.06, Error D of freedom= 6, P= 0.8216). (Across: mean=75.25, Std Dev=32.27 – Corner: mean=79.25, Std Dev=22.39).

The quantitative results show that the only factor that had significant effect on the number of workspace awareness events in the study was task type. Table size and seating arrangement did not have a significant effect on this measure.

4.2.2 Parallel search

When materials were separated from each other on the table, it enabled participants to scan through materials at the same time, i.e. to perform parallel search (See Figure 22).

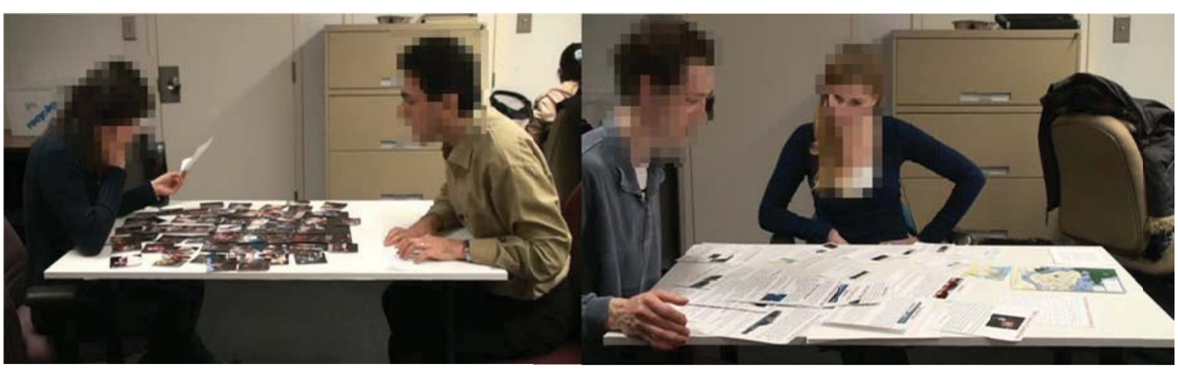


Figure 22: Two examples of parallel searching events on separated materials

Table 9: Parallel search events

Parallel search		Small Table		Large Table	
		Story- Telling	Travel- Planning	Story- Telling	Travel- Planning
Position	**Pair**				
Across	**G2**	44	22	62	18
Across	**G6**	70	20	65	56
Across	**G 7**	73	25	69	97
Across	**G14**	99	14	140	64
Corner	**G10**	32	22	71	72
Corner	**G11**	140	114	159	96
Corner	**G12**	79	22	66	66
Corner	**G16**	55	15	55	20

Incidents of parallel search events were measured and are shown in Table 9. A repeated measure ANOVA test was done to compare the parallel search, across table size and task condition. A QQ-plot shows that the original data does not have a Normal distribution. The Shapiro-Wilk test also gives a test statistic of 0.90 and p-value 0.0076. Therefore, the hypothesis of having normal errors is rejected. By applying a logarithmic transformation[8] to the data set, the distribution becomes roughly normal. The Shapiro-Wilk test endorses the QQ-plot result, yield test statistic of 0.98 and p-value 0.8186 on the transformed data.

Statistical analysis on the transformed data showed that a significant difference exists in the number of parallel search events between table sizes (F=10.43, Error D of freedom= 6, P=0.0179). Participants performed more parallel search on the large table (In logarithmic scale Small table: mean=3.71, Std Dev=0.76 – Large table: mean=4.17, Std Dev =0.57).

No interaction effect was found between table size and task, but a significant difference was found in the number of parallel search event between task types (F=22.70, Error D of freedom= 6, P=0.0031) with more in the story-telling task (In logarithmic scale Story-Telling: mean=4.29, Std Dev= 0.43 – Travel-Planning: mean =3.58, Std Dev=0.75).

[8] Because some values were zero log(x+1) was applied.

A one-way ANOVA was conducted to compare parallel search across seating arrangements. No significant difference was found, (F= 0.14, Error D of freedom= 6, P= 0.7215). (In logarithmic scale Across: mean=3.87, Std Dev=0.76 – Corner: mean=4.17, Std Dev=0.57).

Quantitative analysis results show that table size and task type are significant factors on parallel search events. Seating arrangement did not have any effect.

4.2.3 Serial search

When participants turned over materials from a pile and looked at them one by one, serial search was coded. See Figure 23.

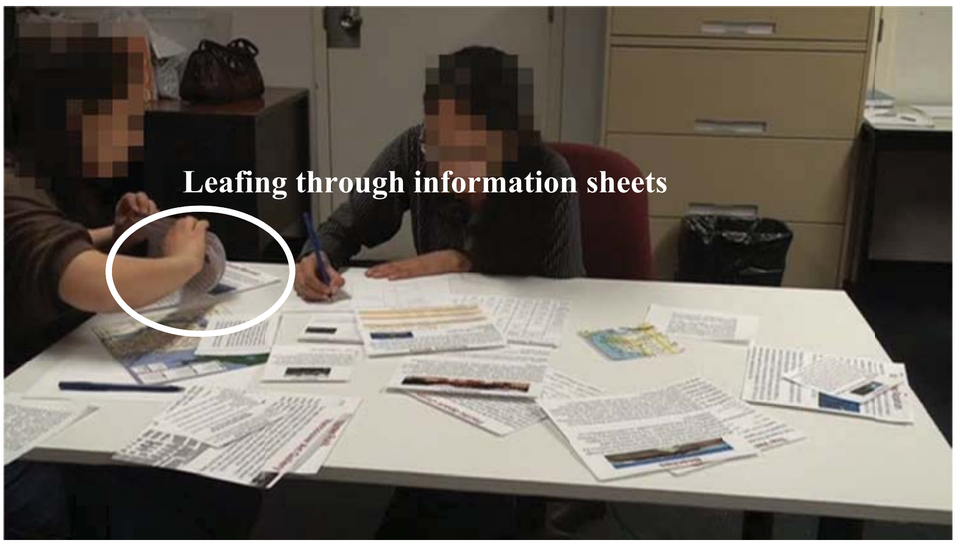


Figure 23: A serial search event

Incidents of serial search events were measured and are shown in Table 10. A repeated measure ANOVA test was done to compare the serial search, across table size and task condition. A QQ-plot shows that the original data does not have a normal distribution. The Shapiro-Wilk test also gives a test statistic of 0.92 and p-value 0.0218. Therefore, the hypothesis of having normal errors is rejected. By applying a logarithmic transformation to the data set, the distribution becomes roughly normal. The Shapiro-Wilk test endorses the QQ-plot result yielding a test statistic of 0.98 and p-value 0.7235.

While a statistically significant difference was not found in the number of serial search case (after data transformation) between table sizes, *a statistical trend was observed* (F=5.73, Error D of freedom= 6, *P=0.0537*). (In logarithmic scale Small table: mean=1.75, Std Dev=0.95 – Large table: mean=1.15, Std Dev =0.92).

Table 10: Serial Search events

Serial Search		Small Table		Large Table	
		Story- Telling	Travel- Planning	Story-Telling	Travel- Planning
Position	**Pair**				
Across	**G2**	4	21	1	14
Across	**G6**	2	7	0	3
Across	**G7**	0	21	0	1
Across	**G14**	18	10	3	3
Corner	**G10**	1	3	15	3
Corner	**G11**	4	9	4	3
Corner	**G12**	1	12	0	1
Corner	**G16**	1	5	0	9

No interaction effect was found between size and task, but a significant difference was found in the number of serial search between task types (F=7.40, Error D of freedom= 6, P=0.0347) with more in the travel-planning task (In logarithmic scale Story-Telling: mean=0.99, Std Dev= 0.95 – Travel-Planning: mean =1.92, Std Dev=0.77).

A one-way ANOVA was conducted to compare serial search across seating arrangements. No significant difference was found. (F= 0.25, Error D of freedom= 6, P= 0.6322). (In logarithmic scale Across: mean=1.54, Std Dev=1.1 – Corner: mean=1.37, Std Dev=0.86).

Based on this analysis, task type had a statistically significant effect on the incidence of serial search. As well, table size may affect the frequency of serial search. Seating arrangement had no statistical effect.

4.3 Chapter Summary

This chapter has presented quantitative analysis results of the major behaviors related to external cognition. The results of statistical analysis on initial and extended codes are presented in Table 11. This table summarizes which independent variables have an effect on each of the coded behaviors.

Table 11: Overall summary for coded events

Coded events	Significant effect between table sizes?	Significant effect between task types?	Significant effect between seating arrangements?
Initial codes			
Above- the table, material use	More on the ***small table***	More in ***travel-planning***	More in ***corner seating*** arrangement
Spatial usage of the tables	More on the ***large table***	More in ***travel-planning***	More in ***across seating*** arrangement
On- the table, Cognitive Tracing	More on the ***large table***	More in ***story-telling***	No
On- the table, Piling	More on the ***small table***	More in ***travel-planning***	No
On- the table, Visual separation	More on the ***large table***	More in ***story-telling***	No
Extended codes			
Work space awareness	No	More in ***travel-planning***	No
Parallel search	More on the ***large table***	More in ***story-telling***	No
Serial search	More on the ***small table***	More in ***travel-planning***	No

Numerical data extracted from videotaped experimental trials were analyzed to determine factors that were significant influencers on participants' interactions. The quantitative results revealed that table size had significant effects on different types of external cognition: grouping and cognitive tracing. In particular, parallel search, serial search, spatial usage of the table, and above-the table materials usage all had significant differences on the two table sizes. The next chapter presents the results of a qualitative analysis of participants' behaviors.

Chapter 5
Qualitative analysis Results

While the quantitative analysis indicates significant factors influencing users' behaviors, it is also important to understand how behaviors change as the result of varying independent variables such as table size, seating arrangement and task type. In this chapter, participant behaviors will be considered. As described in Chapter 3, the video data was coded to identify phenomena of interest. These phenomena were then grouped and labeled using the affinity diagramming data synthesis technique [27]. Finally, the related phenomena were linked to the experimental variable to describe the effects of experimental factors on participants' behaviors.

The chapter is organized as follows. First, several snapshots[9] from the study are presented to demonstrate the quantitative results showing table size effects on external cognition of pairs in the study. These snapshots allow an examination of why piling happened more on the small table, and why the large table fostered visual separation and cognitive tracing in the study. Then, other factors such as table size, seating arrangements and task type, which also affected participants' use of the external cognition, are discussed with sample events from the study.

5.1 External Cognition and Table Size

Quantitative data in Chapter 4 shows that participants exhibited different external cognition behaviors on the small and large tables. The statistical results presented in Chapter 4 show significant differences in each kind of external cognition between two table sizes. Visual separation and cognitive tracing were more common on the large table, while participants tended to use piling on the small table to organize task materials. The qualitative analysis confirmed that table size is a significant factor for triggering two kinds of external cognition, grouping (visual separation and piling) and cognitive tracing. This section explores how table size affected the type and quality of participants' behaviors during their travel-planning and story-telling tasks.

5.1.1 Visual Separation

As discussed in Chapter 2, visual separation is a type of grouping used for external cognition, which helps categorize and understand task materials. In the study, pairs used visual separation by distributing

[9] The snapshots were selected after several times of video analysis.

individual task materials (open categorization[10]) on the table. Participants grouped similar items together without overlapping them to create categories that, in turn, were kept physically separated. By using visual separation, participants did not need to remember items in different categories; instead they could easily refer to the information visually available on the table when needed. As participants were problem solving and thinking, visual separation played the role of external memory by which they could offload categories they created on the table.

This kind of grouping enabled participants to do parallel searching across a number of materials by having visually available materials (open categories) on the table. Parallel searching was helpful for participant's individual cognition as they can easily reference and compare task materials without memorizing task material contents. Furthermore, the exposed materials on the table also facilitated workspace awareness of participants' partners in the pairs and triggered many incidents of collaboration, which may increase group cognition within the pairs.

The following examples demonstrate how pairs used visual separation differently on the two sizes of tables and how the benefits of visual separation increased.

Individual cognition: The ability of participants to visually separate items on the table allows for improved individual cognition. In Figure 24, P20 from G10 spreads materials, which were chosen as potential options for their itinerary, to evaluate them with the instruction sheet as a reference (his left hand is on the instruction sheet). Figure 24 shows him reading through task materials and comparing them to determine the best option for the itinerary. He benefits from the large table's improved support for parallel search, as P20 has more than one itinerary visually available in front of him and he does not need to manually manipulate materials to view them one by one to remind them. In contrast, Figure 25 shows that, participants of G10 were forced to look at the same type of information serially and above-the-table (on the small table) because there was not enough room to spread materials on the table. Although this group had inter-group separation of materials on the small table, there was limited space available to physically separate individual materials inside of the grouped task materials (i.e., to create intra-group separation). On the small table, G10 spent more time leafing through materials, and correspondingly had less opportunity to compare and contrast a large set of visual options from each group of task materials.

[10] Categorized materials while they are separated from each other on the table.

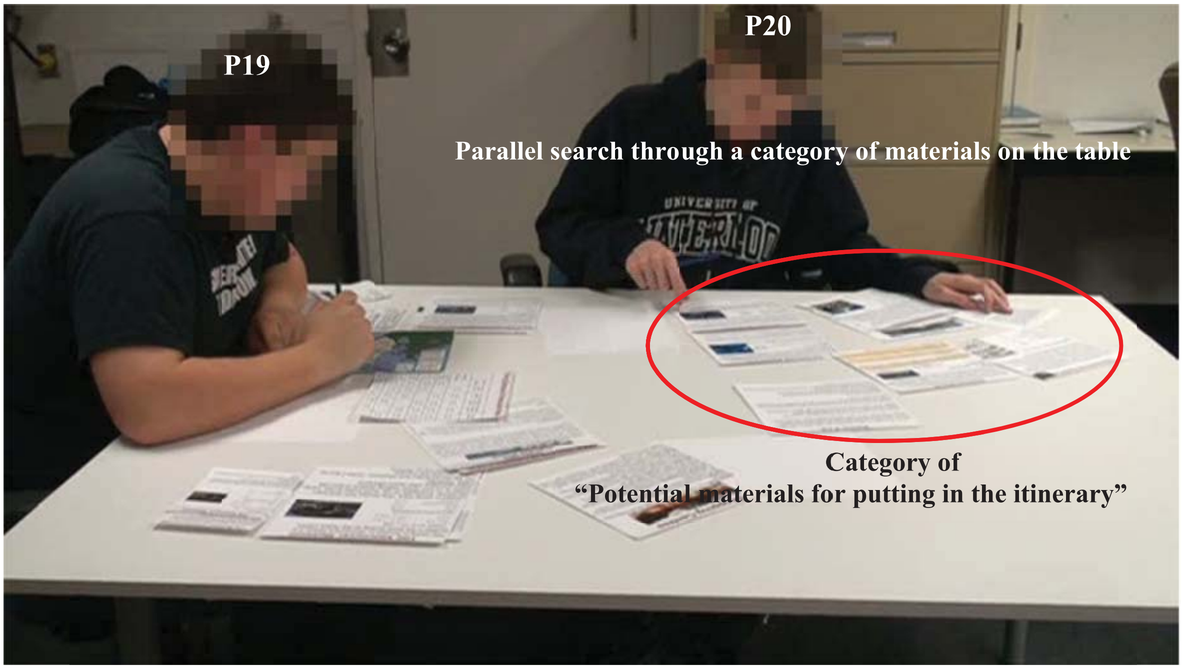


Figure 24: Individual cognition via visual separation on the large table (G10).

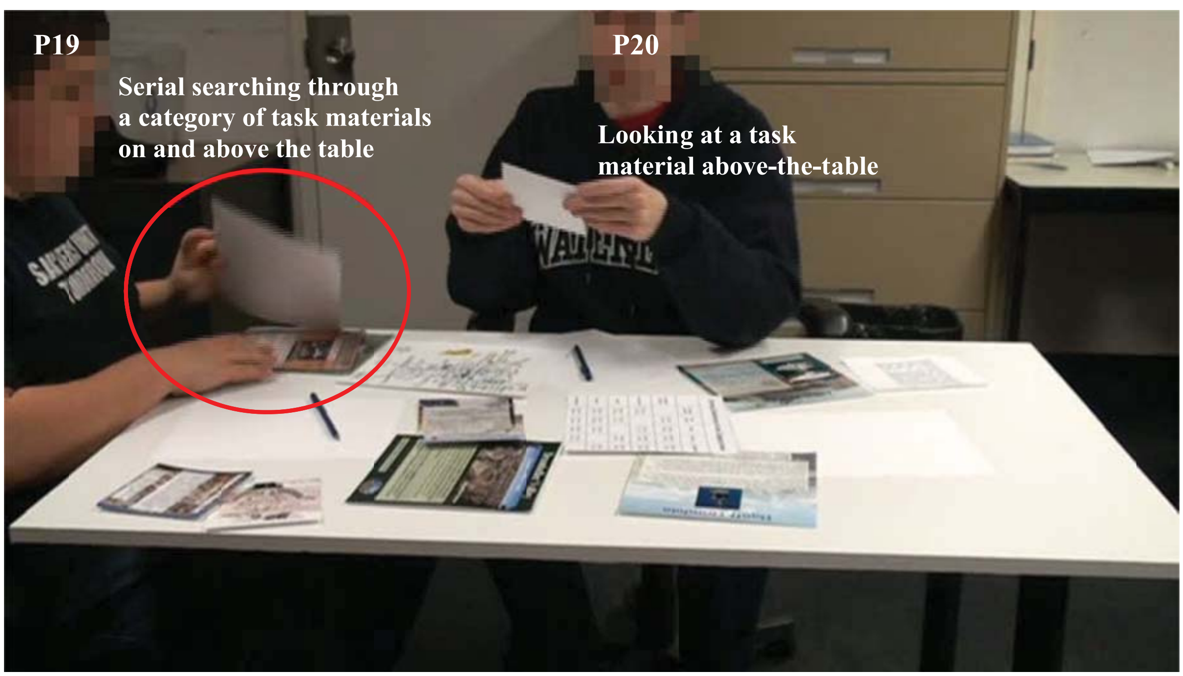


Figure 25: Serial search and above-the-table looking on the small table (G10)

Group cognition: Beyond assisting individual cognition, visual separation also helps group cognition by increasing workspace awareness of participants and promotes of collaboration. The next example illustrates how visual separation helped group cognition between participants of G7.

In Figure 26, P13 and P14 are discussing whether they can match two task materials to use them as a part of the itinerary, while also considering other materials. All materials in Figure 26 are individually separated on the table and P14 is pointing to two of them. The task materials, which P14 is referring to, are visually available for P13 as well, and he can see what his partner is indicating. In this case, expansion of separated materials fostered workspace awareness for P13 and promoted group cognition as visual separation provided a shared reference point for both participants. On the small table, however, G7 could not distribute materials in the same way. As shown in Figure 27, to have intra-group separation of materials on the small table they had to distribute layers of information sheets, which covered each other, allowing only some of them to be visible at one time. Although, G7 still had visual separation on the small table, participants of this group do not have the same opportunity as on the large table to discuss all materials together. Because of limited space and layers of materials, this pair performed significantly more manual search using above-the-table interactions than on the large table.

Figure 26: Group cognition via visual separation on the large table (G7).

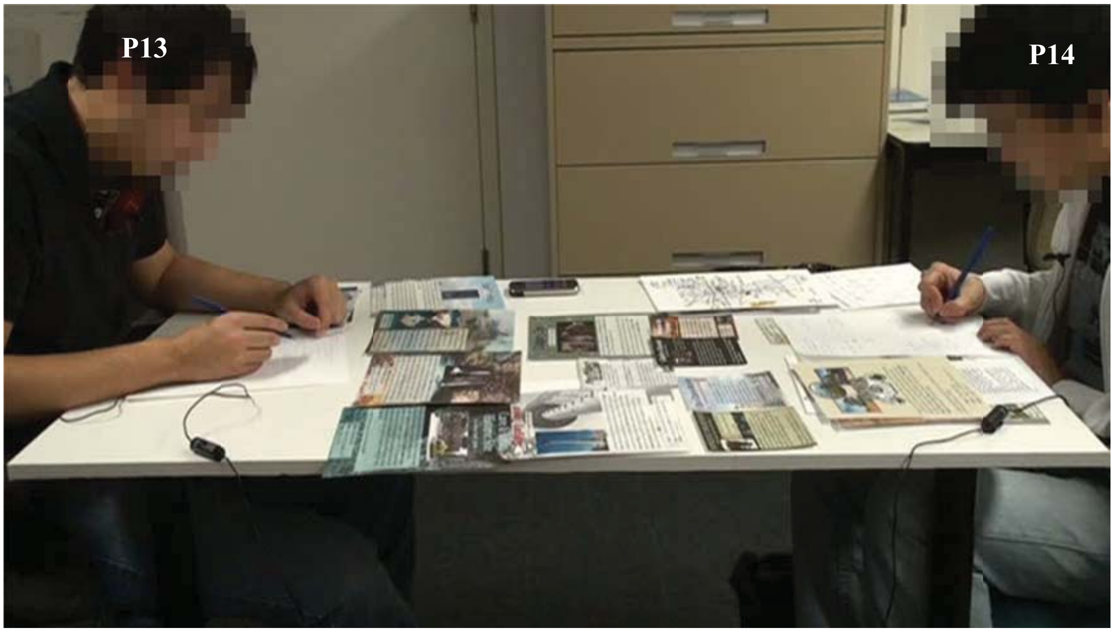


Figure 27: Layers of separated materials on the small table (G7).

G7 and G10's behaviors from previous pictures show that the opportunity for visual separation is reduced on the small table. People used other strategies, on the small table, such as using materials above the table and piling for categorizing task materials and understanding their concepts. However, the large table enables participants to investigate more options at a glance. This ability helps people to compare task materials together by parallel searching through them. Parallel searching of materials helped individual cognition of participants to find specific task materials easily on the table instead of manually searching through layers and piles of materials. Because materials are visually available, participants did not have to memorize the task materials before using them in the solution. Moreover, having open categorization of task materials fostered workspace awareness and participants could see what their partner was doing; this ability increased group cognition for problem solving.

5.1.2 Piling

Piling is another style of grouping of task materials on the table. That involves stacking materials without visual separation (see Figure 28). The video analysis revealed two main reasons for piling:

1. To reduce the complexity of the task, by reducing the number of materials under consideration.
2. To compensate for the lack of space

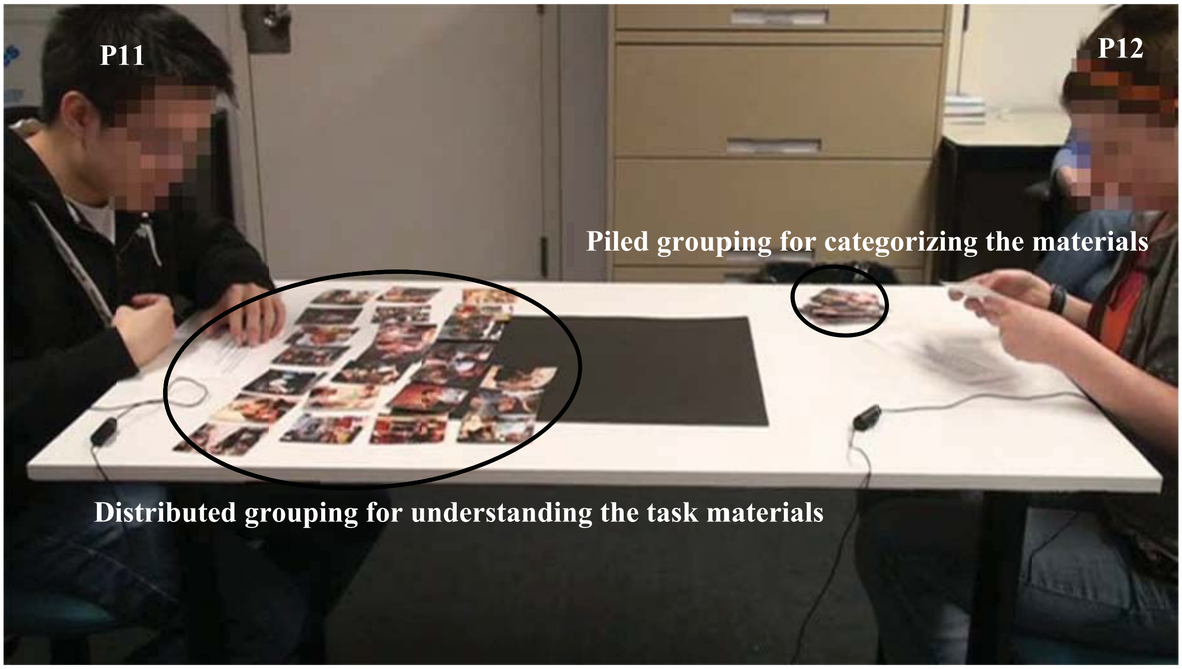


Figure 28: P11 and P12 from G6 are grouping differently on the small table

Piling was helpful to reduce task complexity because pairs could focus on the task materials that had not yet been analyzed. Participants put materials in piles after making a decision about them and looked at the piled materials later only if it was necessary. This use of piling was observed on both large and small tables in the video analysis. In contrast, the use of piling on the table surface sometimes appeared to be a coping strategy for insufficient space on the small table. Piling allowed participants to reduce the space taken up by each category. As reported in Chapter 4 there were significant more piling events on the small table and qualitative analysis supports this result.

As participants of this study were not constrained to use piling to reduce task complexity on both tables, the qualitative analysis focused on understanding how the small table forced people to use piling as a strategy to compensate for limited space. The following describes why pairs used piling more than visual separation on the small table.

5.1.3 Visual Separation versus Piling

The two examples below demonstrate how pairs exhibited different grouping strategies on the small and large tables when doing story-telling and travel-planning. Figure 29(a) shows both inter- and intra-group separation of materials on the large table. Two pieces of task materials as reference items (a map and a distance table) plus chosen materials by P20 for making an itinerary, are almost completely separated from each other (intra-group separation) in front of P20. Moreover, the other five groups of materials in front of P19 are separated (inter-group separation) and materials in each group overlap slightly but the titles of each item are still clearly visible. In Figure 29(a) P20 is looking at the chosen materials in front of him, while P19 can also see what he is working on, fostering workspace awareness. However in Figure 29(b), on the small table, just inter-group separation can be seen, and material in each group is stacked into piles and never been opened. Furthermore, P19 is looking at the chosen material above the table to compensate for the limited workspace.

As can been seen from the Figure 28 and Figure 29, two styles of resource categorization on the tables led to different ways of investigating options for travel-planning. Figure 30 shows an example from the story-telling task, which compares the small and large tables to show how they provide different grouping styles for categorization. On the small table (Figure 30 (a)), participants looked through materials above the table or they leafed through items on the table one by one from piles (serial search). However, on the large table the available space allowed intra-group separation, facilitating parallel search on the table (Figure 30 (b)).

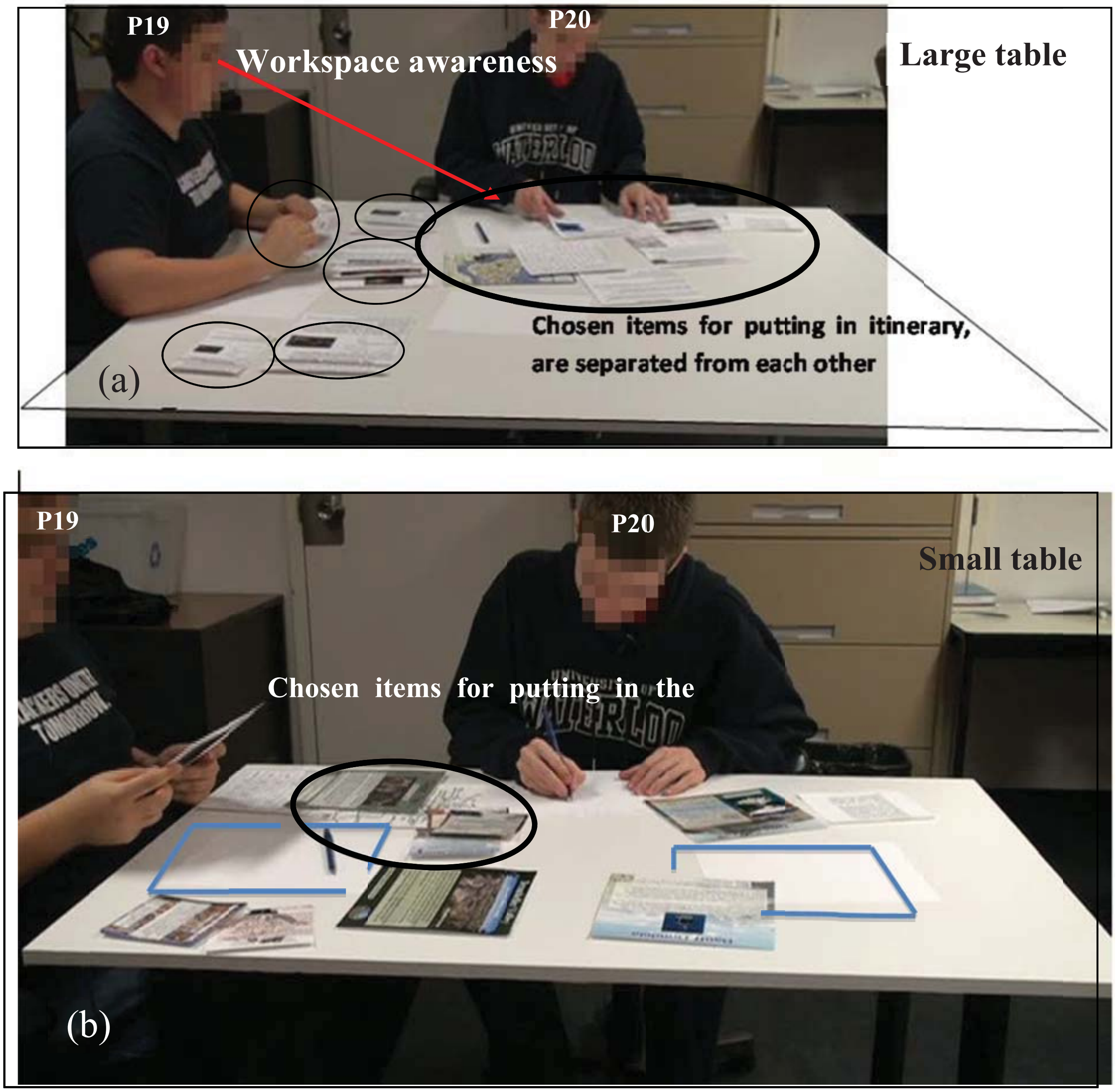


Figure 29: (a) Parallel search (b) versus serial search (G10) – blue rectangles are white sheets

Figure 30: (a) piling versus (b) visual separation (G2)

In Figure 30, participants had already made a storyline and they were searching for new pictures to add to their story to improve it. Based on the definition provided in Chapter 2, they were in the third phase of understanding and problem refinement. On the small table, pictures, which were not in the storyline, were stacked in two different piles. In Figure 30(a), P3 scans through pictures of those piles serially above the table while P4 reviews the story. However, in Figure 30(b) on the large table, P3 and P4 perform a parallel search through visually separated pictures together.

This group used the same amount of space for making the storyline on the story board on both tables, but on the large table the available space on the sides was almost twice as big. Materials on the sides of the story are shared, so participants can see what their partners are doing and they can talk about materials much more easily. However, on the small table material was typically placed in the personal area of one participant in two piles, which hinders workspace awareness and shared ownership.

As a result, pairs usually used piles for categorizing their materials on the small table as a coping strategy for limited table space, which led to serial search during the understanding phase of the task process by leafing through materials in the piles.

5.1.4 Cognitive Tracing

By manipulating and modifying the task materials (and/or piles of materials) into a meaningful order, pairs performed cognitive tracing of materials to help creating a solution. As reported in Chapter 4 cognitive tracing behavior was more prevalent on the large table. On the small table, cognitive tracing occurred more often above the table by manipulating, sorting, and sometimes passing information sheets.

As Figure 31 shows, G6 demonstrated an extreme case of cognitive tracing on the large table during the travel-planning task. This pair created an entire draft of their three-day itinerary on the table before committing it to the paper. They established three columns of information sheets on the table, one for each day of the visit. They rearranged the information sheets around and swapped in and out other information sheets from distributed materials as they discussed the feasibility and their opinions for the itinerary. Finally, they wrote down the plan once they were satisfied.

Though only three pairs created the entire travel plan on the table before committing it to paper, many smaller episodes of such ordering, reordering and categorization was observed on both tables. However, manipulation of information directly on the table surface was more common and easier to accomplish on the large table. To perform cognitive tracing of materials, pairs needed to reserve some part of the table area for organizing material. The way pairs manipulated and managed materials on the table while doing cognitive tracing was different on tables of different sizes. Two examples below demonstrate this difference.

Figure 31: Cognitive tracing of the itinerary on the large table (G6).

G7 in Figure 32 is a case for comparing the manipulation of materials for cognitive tracing with the one by G6 in Figure 31. In order to create the itinerary layout, G7 was required to overlap and pile other task materials. In Figure 32, three rows of the itinerary were organized in the middle of the small table on top of other material. However, G6 had enough space for separating materials on the large table, so they could create the itinerary layout and also search through separated materials to optimize their itinerary.

The space around the itinerary layout in Figure 31 is more suitable for visual separation and parallel searching than the space available in Figure 32. In Figure 31, G6 has enough shared space for parallel searching among the additional materials, but the lack of space on the small table forced G7 to create piles and perform serial searching.

Figure 32: Cognitive tracing of the itinerary on the small table (G7)

Figure 33: Cognitive tracing of a story line on the large table (G16).

Figure 33 and Figure 34 demonstrate the use of cognitive tracing during the story-telling task. In these figures G16 is ordering materials into rows for creating a storyline. In Figure 33, on the large table, the draft of the storyline is located in the shared area between participants where both can reach it. However, in Figure 34(a) on the small table, the draft of the storyline is to the left of P32, and not easily accessible to P31. Figure 34(b) shows P32 moving the storyline onto the story board. In this figure, participants in G16 made space for moving the storyline to the story board by pushing the remaining pictures toward P31, which resulted in overlapping pictures. This caused the search area to become smaller, and they had to shuffle through photos when searching. On the other hand, on the large table in Figure 33, there is sufficient space to have both ordered photos in the story line and remaining materials visually separated in front of the participants. Having all photos available for G16 on the large table was useful, as the group went back and forth between the phases of solution making, understanding, and refinement of the problem leveraging visual separation of task materials.

In summary, the quantitative and qualitative data analysis, support the conclusion that the more space available on the larger table fostered the use of external cognition during for problem-solving tasks. The large table facilitated external cognition because it provided external memory for pairs through visual separation of task materials. This use of external cognition, in turn, fostered individual and group cognition. The larger space accommodated more task material separation, which facilitated parallel searching, cognitive tracing, and workspace awareness.

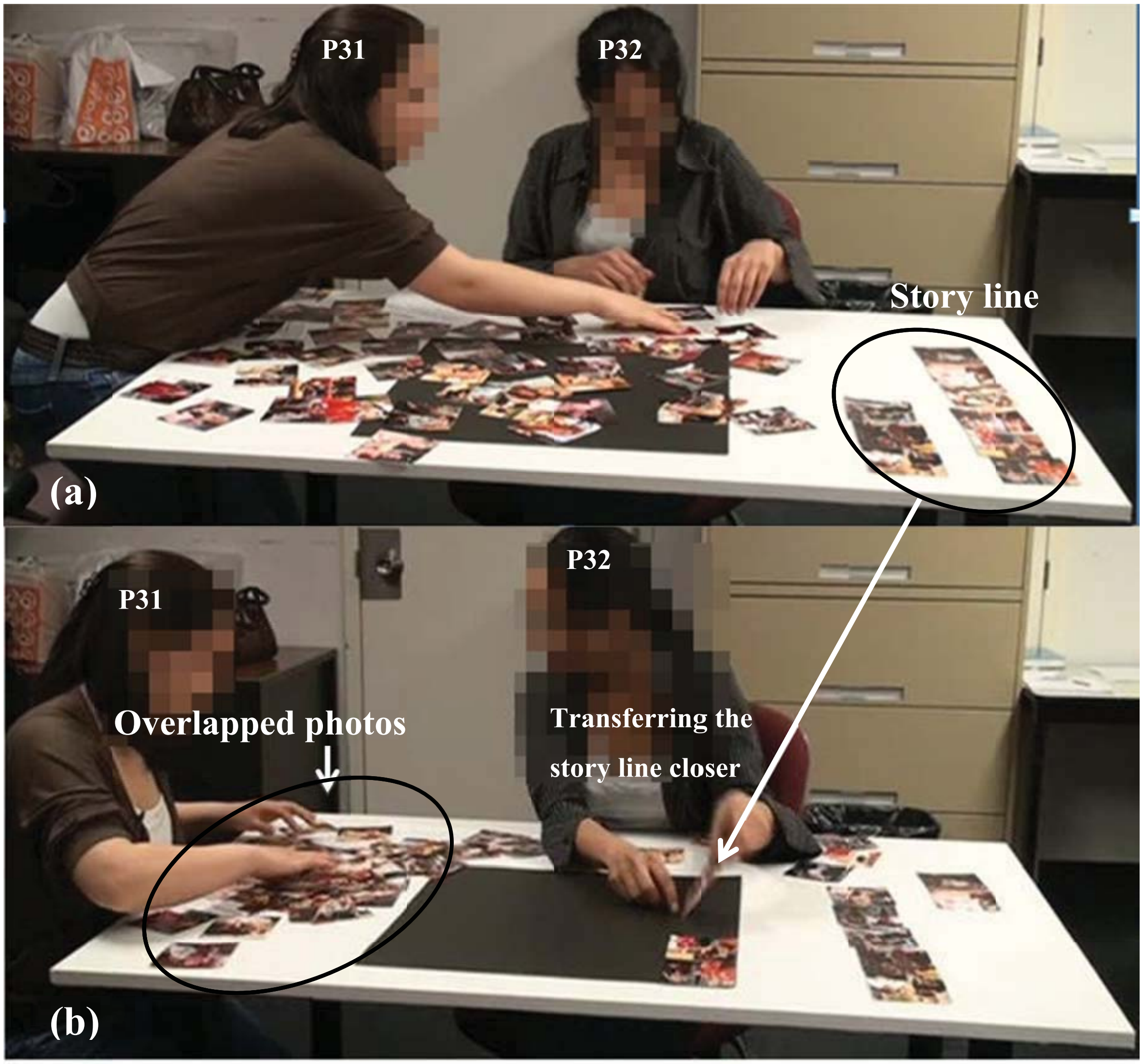


Figure 34: Cognitive tracing of a story line on the small table (G16).

5.2 External Cognition and table size, considering seating arrangement

In addition to table size, pairs' seating arrangement also affected external cognition. Though the quantitative analysis showed no significant differences in the kinds of external cognition (visual separation, piling, or cognitive tracing) between the two seating arrangements, the qualitative analysis revealed differences.

The size and location of personal and group territories differed between the two seating arrangements, which led to differences in both independent and joint work. Moreover, the different seating arrangements changed the amount of accessible space on the tables, which resulted in different spatial usage between pairs.

The following subsections discuss the differences in tabletop territories and accessibility of materials between the two seating arrangements, and how these two factors influenced the use of external cognition during the study.

5.2.1 Territoriality

Pairs used different portions of the tables for different purposes. Usually the area within reach in front of each participant was used for independent task activities while the shared area (the location of which depended on the seating arrangement) was used for joint task activities. These findings are consistent with findings of Scott and Carpendale [49] who defined the area for independent work as a personal territory and the area for joint activities as a group territory. As reported by Scott and Carpendale, the spatial territories were dynamic and fluidly changed as activities evolved.

Participants used their personal territories to temporarily disengage from group work to perform independent activities, such as reading, searching, and categorizing task materials (similar to participants in Scott and Carpendale studies [49]). Moreover, sometimes participants divided the task activities and had each participant complete part of the work, demonstrating mix-focused collaboration [57]. The use of these strategies in this study indicates that having enough space for personal and group activities are important to collaborative problem solving.

5.2.1.1 Personal territories

The personal territories were defined within the boundary that participants could extend their hands near their body on the table. As participants could move along the table side that they sat, the dotted lines in Figure 35 and Figure 36 show the boundary of each personal territory and the red lines are samples of personal territories. The amount and location of personal territory for each participant depended on the seating arrangement and the table size, which participants were working on. The size and shape of personal territories defined by participants were not a constant area; participants expanded their individual territories during the problem-solving tasks as needed.

Figure 35 and Figure 36 show the location of personal territories for each participant in two different seating arrangements. The distances between participants and the available area in front of each participant played important roles for the size of personal territories. In the across seating arrangement, the distance between participants on both table sizes was the same, 124cm. In this seating arrangement, each participant had a table edge of the same length in front of him/her, 77cm on the small table and 154.5cm on the large table. Conversely, in the corner seating arrangement the table edge in front of each participant was different depending on both table size and the participant's individual seating position (see Figure 35). On the small table, one participant had a table edge of 77cm and the other one had 124cm in front of him/her; on the large table, one participant had a table edge of 124cm and the other one had a table edge of 154.5cm. As participants in the corner seating arrangement readjusted their position along the side of the table, moving a bit to the left or right, the relative distance between participants did not remain constant across groups.

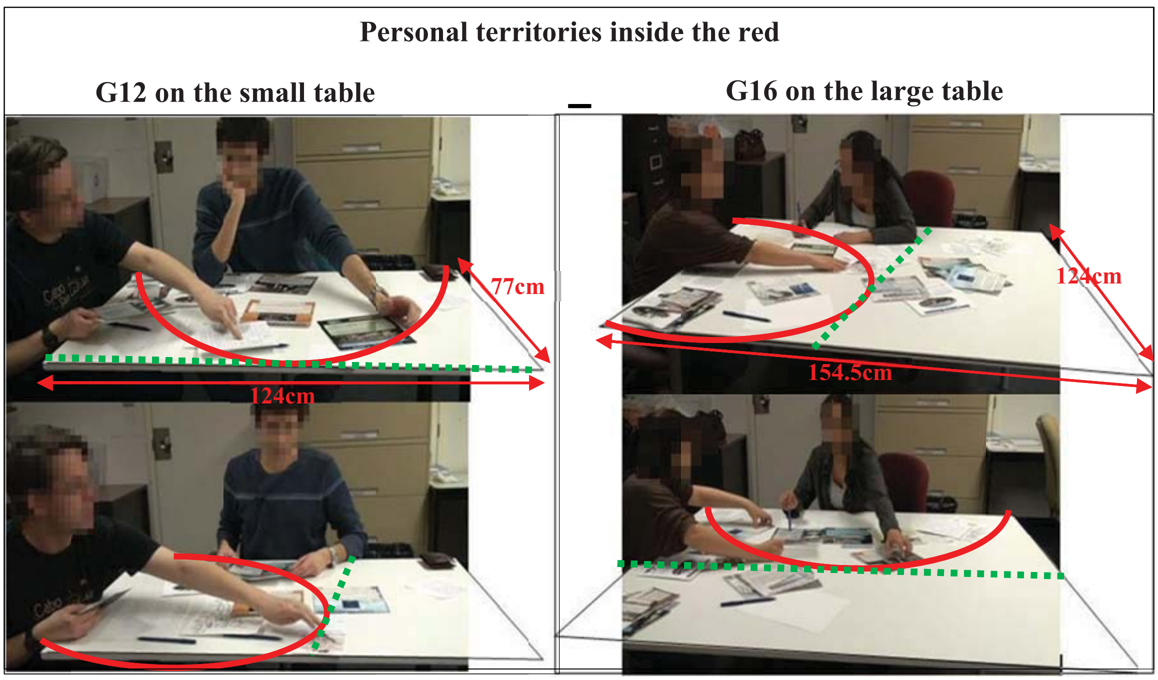


Figure 35: Personal territories in corner seating arrangement on small and large tables

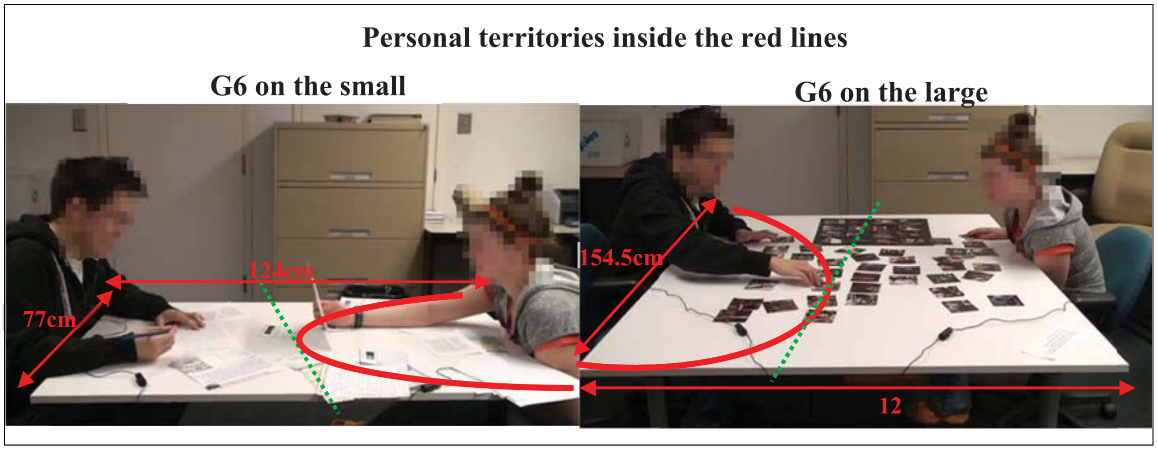


Figure 36: Personal territories in across seating arrangement on small and large tables

On both table sizes, participants in the corner seating arrangement had less personal space than those in the across seating arrangement because of the overlap area in the corner between them. The reduced personal space in this arrangement affected pairs' independent task activities and they could not apply visual separation in this arrangement as much as the across arrangement on the same table size.

Large table: Figure 37 shows independent activities of two pairs of participants taking place in their own respective territories. This picture illustrates how participants in two different seating arrangements defined their personal territories and to what extent they expanded the area for themselves. Figure 37(a) shows that in the across seating arrangement each participant can extend their personal area across the width of the table. On the other hand, Figure 37(b) shows that participants cannot easily use the whole length of the table because part of their personal territory overlapped with their partner's personal territory. These examples demonstrate that a corner seating arrangement provides less room for individual use of visual separation. This limited room for visual separation due to the corner seating arrangement was seen on both small and large tables.

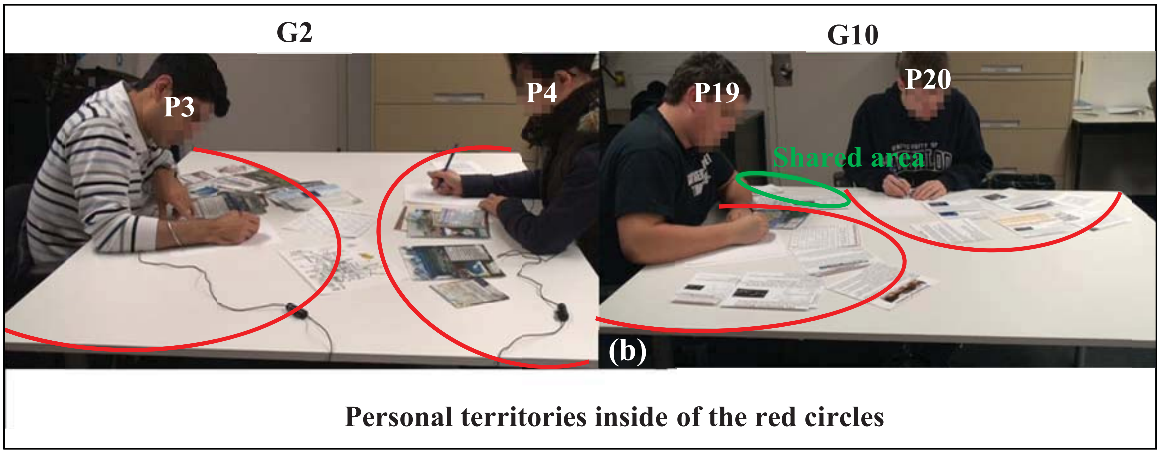


Figure 37: Individual taskwork is performed in personal territories on the large table

Small table: As discussed in Section 5.1, when participants worked on the small table they did not have the same opportunity for visual separation and cognitive tracing as they had on the large table. The territoriality analysis in this study supports this finding and expands it to show that this effect may increase when people sit in the corner seating arrangement on the small table.

Figure 38 shows two groups working on the small table using visual separation. P24 in Figure 38(a) distributed some information sheets beside each other in front of himself, which caused P23 to move to the right side of the table with just half of the table width available as his personal territory. Howevere, Figure 38(b) shows that each participant in G7 had his own personal area fully available to him.

Figure 37 (b) and Figure 38(a) demonstrate that the corner seating arrangement on both tables restricted participants' use of the complete boundary of their personal territory. The participants in Figure 37(b) did not use the shared area, but Figure 38(a), P24 occupied that specific spot and used the whole boundary of his personal territory, which restricted his partner's use of his own boundary for his individual work.

As a result, part of the table in the corner seating arrangement was shared between participants which limited personal teritories of one or both participants in the pairs. This constraint in the corner seating arrangement is one reason for the significant statistical difference in above-the-table materials usage between the corner and across seating arrangements, which showed a greater usage in the corner seating position (see Chapter 4). This means that each participant in the corner seating arrangement needed more effort to scan items, and was limited in the availability of information on the tables in comparison with across seating arrangement.

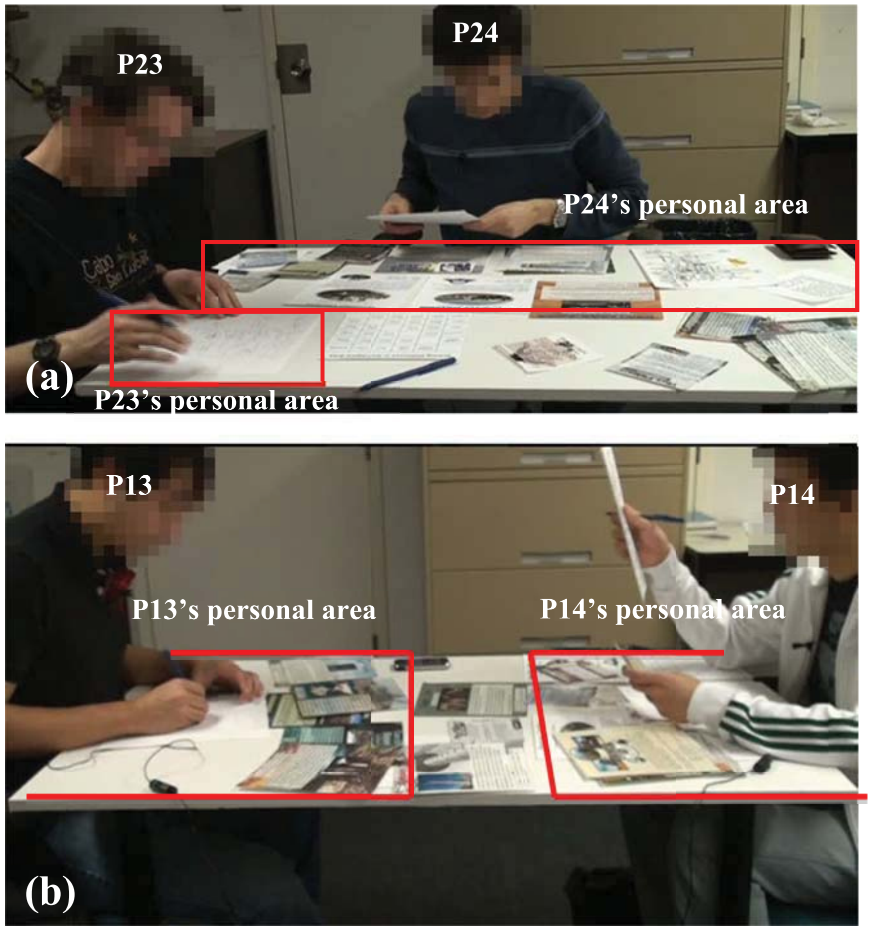


Figure 38: Mix-focused collaboration and personal territories on the small table

5.2.1.2 Group territory

Most of the time group territories were defined in the shared area between participants of pairs. The location of shared space changed between seating arrangements. When pairs sat in the corner seating arrangement, part of their personal territory was taken up by space shared with their partner (see Figure 39(a)). However, when they sat across the table, the shared space was in the middle of the table and was separated from personal space. In both seating arrangements, the location and size of group territories changed over time as needed.

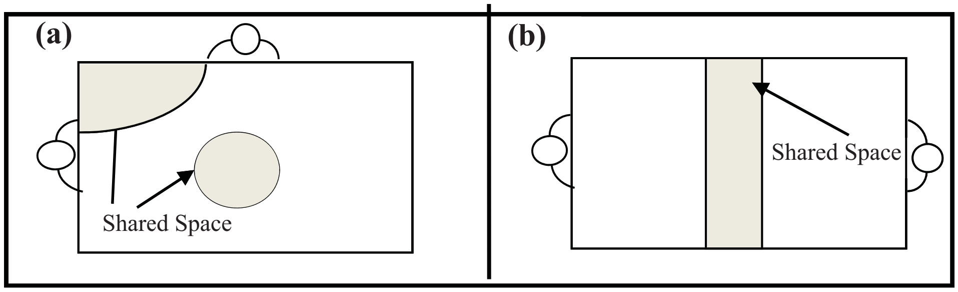


Figure 39: Shared space in two seating arrangements

Across seating arrangement: As shown in Figure 40, participants from two groups defined the shared area between each other as a group territory and are doing a joint activity in that area. Sometimes, pairs did not pre-define a group territory on the table, as seen in Figure 40. In Figure 41, P13 and P14 spread task materials in their own personal territories for individual investigation. These personal territories occupied part of the shared area in the middle of the table and they did not initially reserve any space on the table as a group territory. In Figure 41, they are collaborating on a piece of material in P14's personal territory in the middle of the table and they are temporarily using that area as a group territory.

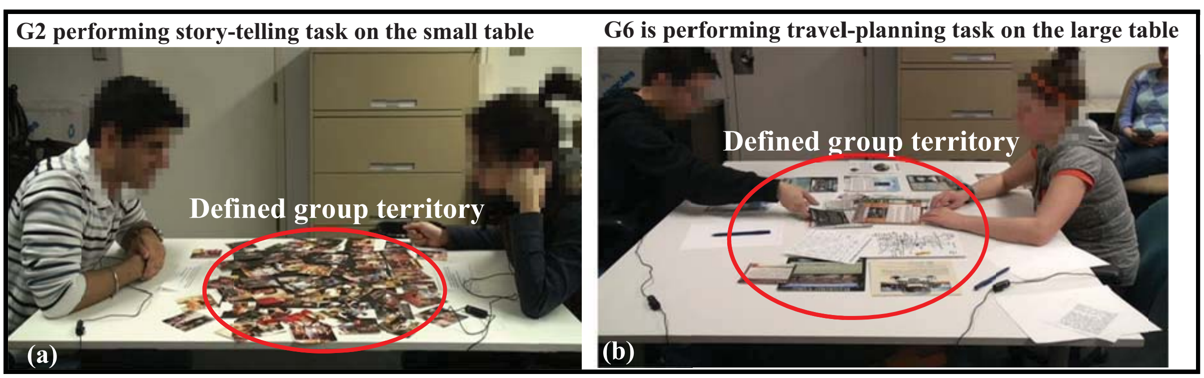


Figure 40: Group territories at the shared area in the across seating arrangement

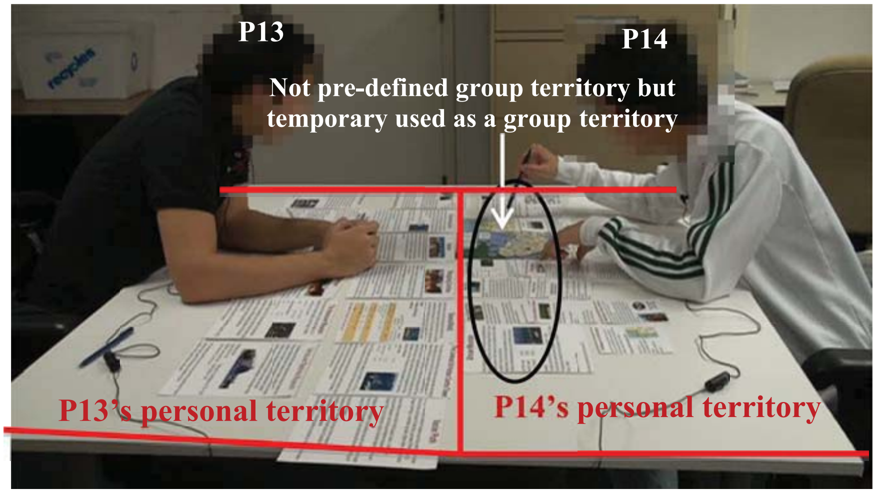


Figure 41: Joint activity in the personal territory

Corner seating arrangement: Similar to the across seating arrangement, pairs usually used shared areas of the table as group territories in the corner seating arrangement (Figure 42).

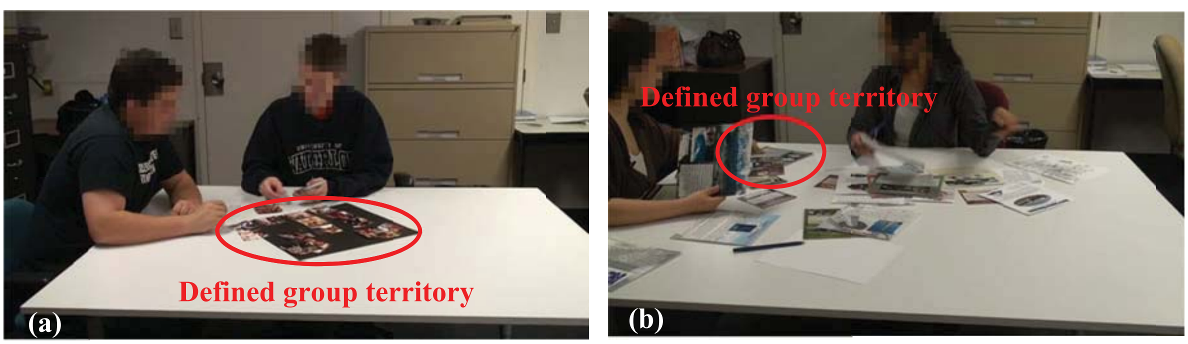


Figure 42: Group territories in the shared areas between participants in corner seating arrangement

In the study, participants in the corner seating arrangement sat close together and they could share task materials easily. As a result this kind of seating arrangement facilitated joint activity better than the across seating arrangement. Each participant was able to adjust the orientation of materials and his/her seating position so that both could easily see materials in the defined group territories. Figure 43(b) shows one participant standing in his position to better scan the photos with the same orientation. However, when participants sat in the across seating arrangement they could not orient all materials toward both participants simultaneously, see Figure 43(a). Participants reoriented materials or passed them between each other for joint activities.

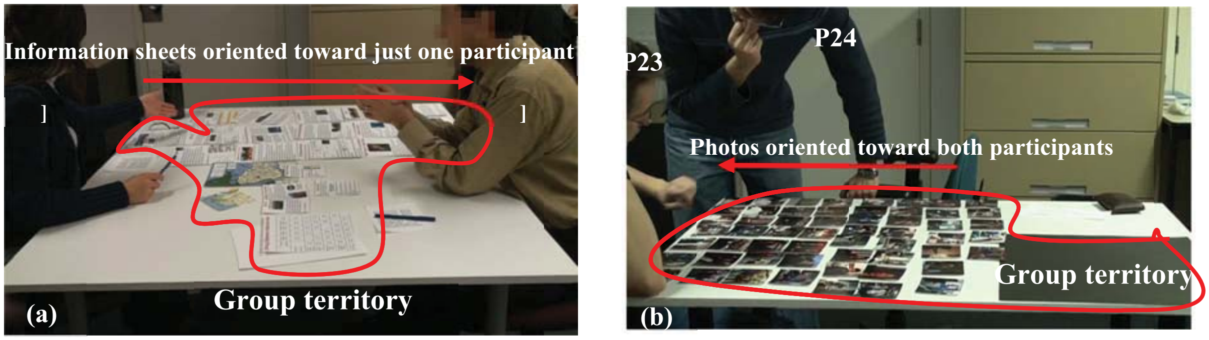


Figure 43: Group territories on the tables other than shared area

(a) Information sheets oriented toward P6 are difficult for P5 to see
(b) P24 can easily see information sheets oriented toward P23

As a result, the corner seating arrangement provided more useful space for group territory and joint activities, but it impeded individual activities. This meant that the corner seating arrangement, specifically on the large table, was a better environment for workspace awareness by facilitating visual separation with the proper orientation of task materials for both participants. On the other hand, participants of pairs in the across seating arrangement had materials oriented towards him/herself and the different orientation affects the common ground between participants on the table. The across seating arrangement allowed larger personal territories, and pairs had an easier time organizing individual work through the increase in available space.

5.2.2 Accessibility

As was mentioned above, typically pairs tried to maintain both personal and group territories. In the study, there were some areas on the tables, which were not easily accessible to one or both participants, though lack of space sometimes caused participants to use those areas as personal or group territories. However, areas on the table that were extremely inaccessible were not used at all. Figure 44 approximates the areas that each participant *could not* access in each seating arrangement.

The area outside of participants' immediate arm extensions (round dashed lines) is the inaccessible area. The straight dashed lines in Figure 44 show all accessible areas in the seating positions of participants along their assigned tableside.

To accomplish their collaborative problem-solving tasks, participants needed to work together in the group territories and be aware of each other's materials and activities in the personal territories. Because of this, visibility and availability of task materials for participants was important. Having materials on the table too far away to see properly resulted in decreased workspace awareness of participants or decreased ability for visual searching.

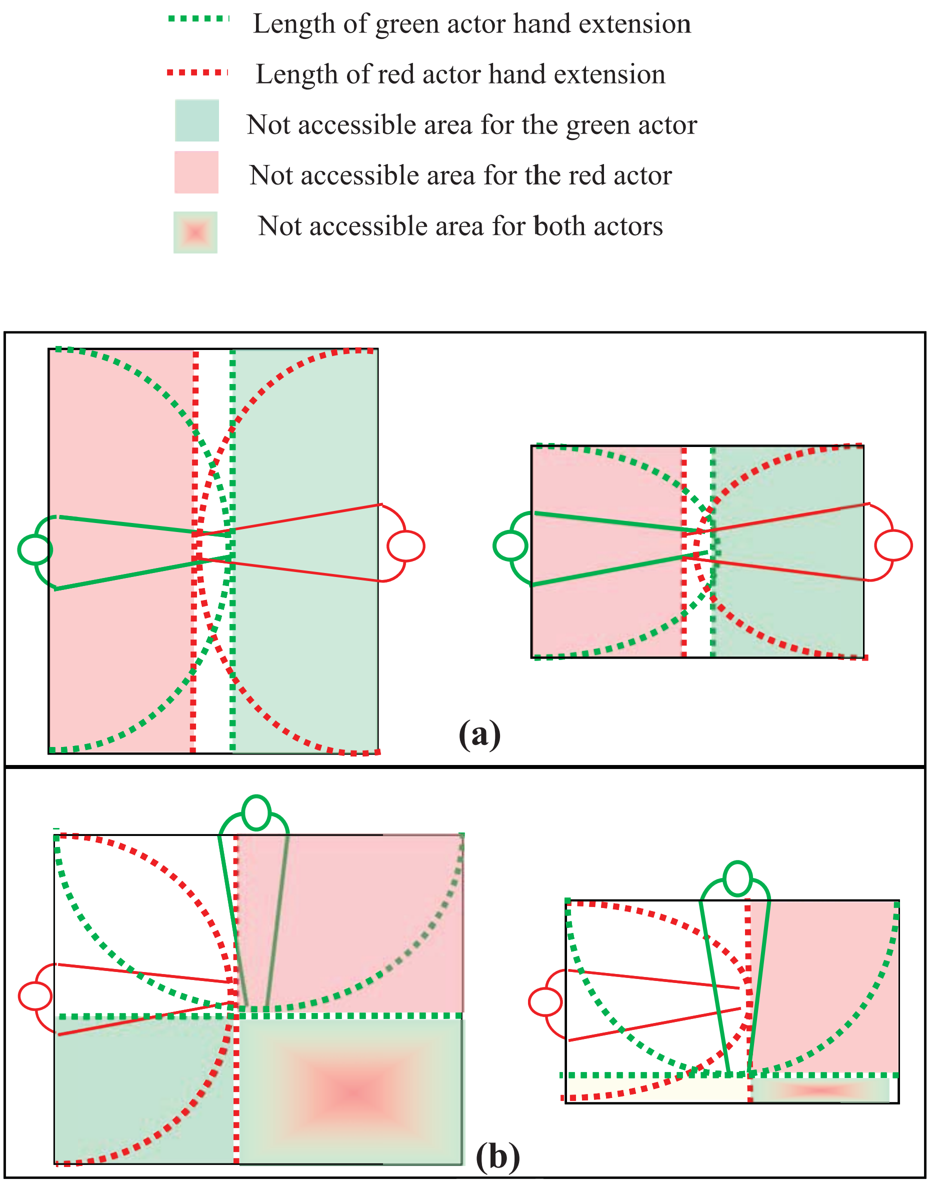


Figure 44: Not accessible areas for participants in two seating arrangements: (a) across (b) corner.

5.2.2.1 Accessibility in the across seating arrangement

Access to partner's personal territory: In the across seating arrangement, participants could define separate personal territories on the table in front of themselves. As shown in Figure 44(a), each participant could access the parts of his/her partner's personal area, which was close to the group territory (if it was expanded by the personal territory boundary, dashed lines in Figure 44(a)), but not the entire personal territory. In the across seating arrangements the accessibility problem existed in both table sizes because the distance between the participants in each pair was the same regardless of table size. Figure 45 shows two snapshots of the study in which P3 and P11 have problems reaching information sheets in their partner's territories on the small and large tables. This increased the number of above-the-table interactions used to cope with this problem. Figure 45(a) shows P3 looking at an information sheet while his partner keeps it above her personal territory and reoriented toward P3.

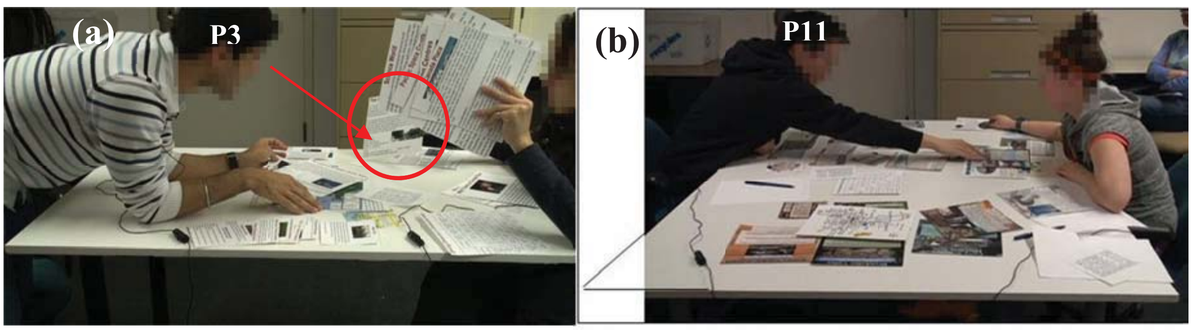


Figure 45: Accessibility problems in the across seating arrangements on both table sizes on partner's personal territories

Access to group territory: In the across seating arrangement, the group territory was defined in the middle of the table where both participants could extend their hand to reach materials. Pairs did not have any problems accessing the group territory. This may indicate that the across seating arrangement was a better configuration for joint work between participants.

5.2.2.2 Accessibility in the corner seating arrangement

Access to partner's personal territory: In the corner seating arrangement, one corner of the table was shared between participants and that area would sometimes be defined as a part of the personal territory for one or both participants because it was easily accessible for both. In this case, the other participant could easily see his/her partner's activities and materials in that specific area. However, the other part of that partner's personal territory was not visible and accessible for him/her (see Figure 44(b) red and green colors inside each participant boundary). This problem was more prominent on the larger table, as each participant had a larger width in front of him or her.

Figure 46 demonstrates the accessibility problem on the large and small tables. P32 and P21 are trying to reach materials in a part of their partner's territory, which cannot be easily seen from where they sit. To solve this problem, these participants asked their partners to pass materials in that area to them.

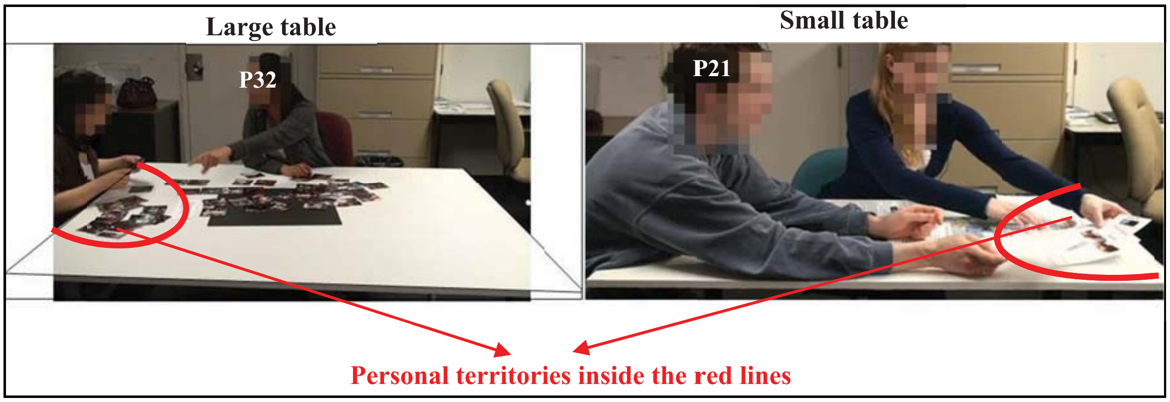


Figure 46: Accessibility problem in the corner seating arrangement on both table sizes on partners' personal territories

Lack of visibility of actions and materials located in each partner's personal territory hindered sharing of task materials and decreased the workspace awareness on the table for participants working collaboratively.

Access to group territory: In the corner seating arrangement**,** the accessibility problem was not limited to the partner's personal territories. Pairs also had problems accessing the group territories. In this seating arrangement, when the group territory was expanded to the middle of the table, accessibility to this area became difficult for at least one participant. The participant sitting along the longer width of the table could access more of the group territory on the table because he or she was closer to that area. However, the other participant sitting along the shorter side of the table could typically only access approximately half of the area in front of him or her. So, when some or all of the group territory was defined further for this participant, the pair had problems working together.

In Figure 47, P31 and P21 both sit on the shorter side of their respective tables and have problems reaching materials in the group territory. To address this problem, each pair had different strategies. P21's partner kept one information sheet above the table to help P21 read it. P31 stood and leaned on the table to reach that part of the table, and later the pair decided to eliminate the group of photos loosely scattered on the table, and make space on the middle of the table to move the story line into an area equally accessible to both participants.

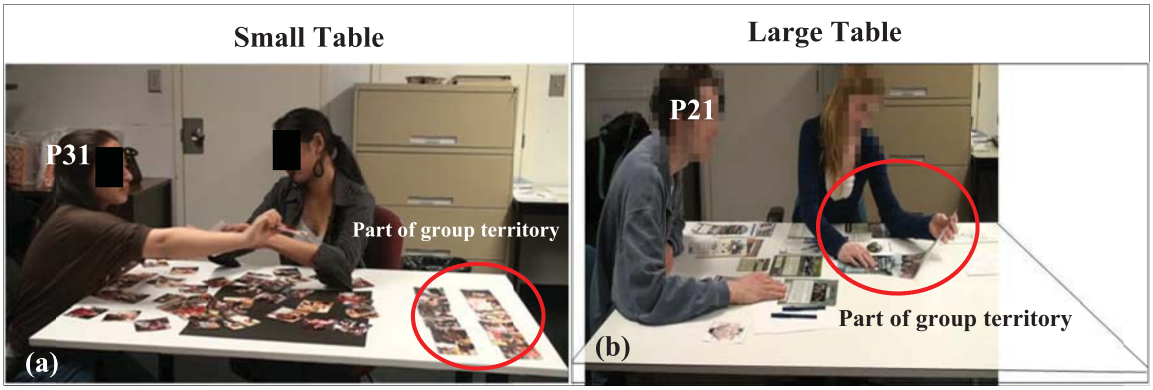


Figure 47: Accessibility problem on group territory in corner seating arrangement on both sizes of the tables

Inaccessible area: Another accessibility problem in the corner seating arrangement was related to the corner opposite the corner shared by participants. This area was not easily accessible for both participant of the table. On the large table, participants could not even access that area by leaning on the table. Pairs in thirteen out of sixteen trials in the corner seating arrangement did not use this area (see appendix H). Participants in the remaining three trials were seated on the small table and the area was in reach of one participant (the one who sat along the longer side of the table).

It can be concluded that in the across seating arrangement, pairs used more area on the table and had more opportunity for visual separation and cognitive tracing. The statistical analysis in Chapter 4 also supports this difference and shows that spatial usage of the table was less in the corner seating arrangement because some areas on the table were not easily accessible, hindering use of those areas. Additionally, participant use of above-the-table materials was more frequent in the corner seating arrangement, as a way of coping with limited accessible space. These quantitative and qualitative results verify that the corner arrangement provided less opportunities for visual separation and parallel search, compared to the across seating arrangement.

5.3 External Cognition and table size, considering task type

In this study, two different problem-solving tasks, story telling and travel planning, were performed on both large and small tables. The materials used in each task differed in number, size, and content. Pairs worked with small photos in the story-telling task but different sizes of information sheets, including images and text, in the travel-panning task.

The number and size of task materials affected the amount of territories, spatial usage of the table, and numbers of piled and above-the-table materials, which led to differences in the ways pairs, exhibited external cognition. The following subsections expand on the observed task material factors and discuss how these factors influenced pairs' external cognition behavior.

Story telling: Materials provided for the story-telling task included a storyboard (45cm x 45cm) on which pairs could construct their stories and fifty-six photos, all of the same size (9cm x 9cm). In this task, pairs had to present their final solution as a sequence of photos. Although the pairs were not obligated to make the story on top of the storyboard, all of the pairs made or transferred the story onto it. Pairs could spread photos and the storyboard on the large table without overlapping (see Figure 48(a) and Figure 48(c)). However, on the small table, pairs could not easily separate the storyboard and photos without any overlap. Figure 48(b) and Figure 48(d) show that although G7 and G12 have visually separated all photos on the table, they do not have space to put their hands on the table and work comfortably.

Because each photo in the story line depends on the previous and next ones, participants needed to talk about photos with each other and make decisions about the order of photos. The videos analysis revealed that in this task six out of eight pairs passed through all phases of the task process, described in Chapter 3 (understanding, categorizing, and making solution), together as joint activities. In this task, pairs had more joint activity than independent work, and the large table supported joint collaboration in this task better than the small table because it fostered workspace awareness via visual separation.

The following two examples show how pairs used the space for doing joint work on the large table and how the small table hindered working in the group territories together, specifically in the phase of problem understanding and problem refinement (all pairs on both tables did the third phase of problem-solving, solution making, together).

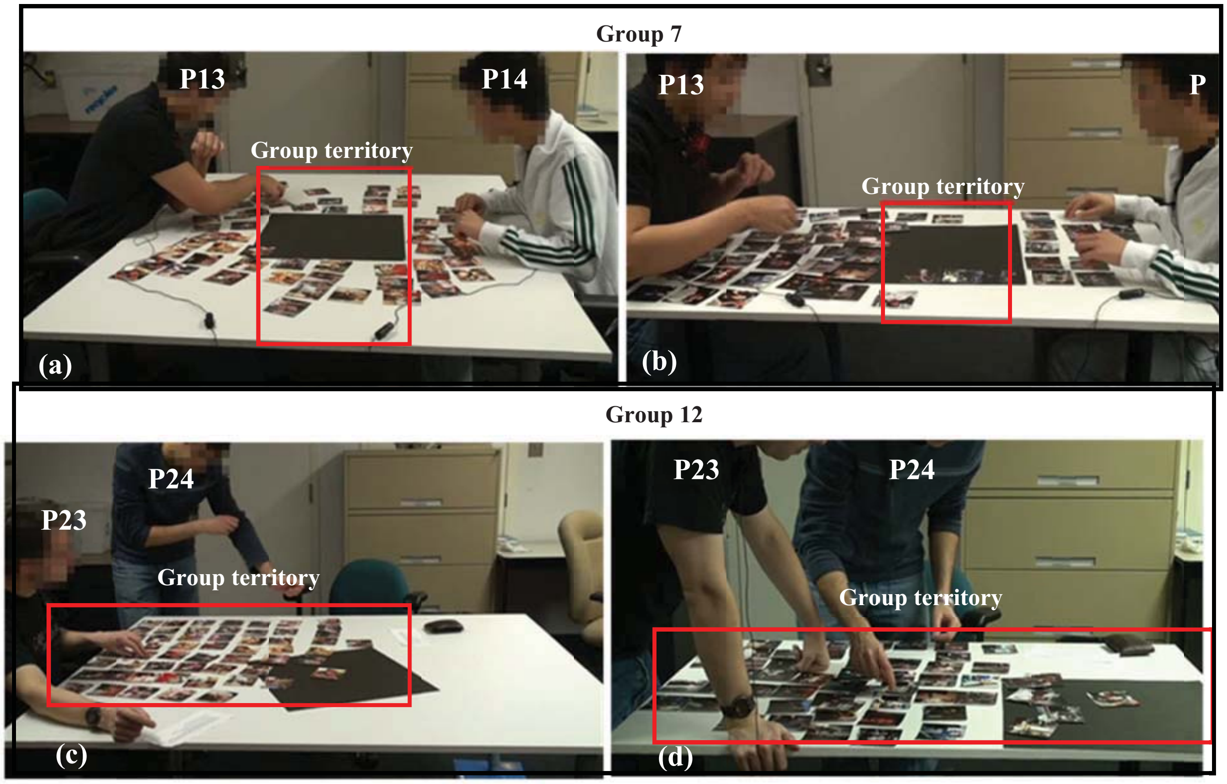


Figure 48: Story-telling on small and large table with across and corner seating arrangement

Figure 48 (a) and Figure 48(b) show that G7, in the across seating arrangement, put the storyboard in the middle of the table to evolve the story. In this seating arrangement, the middle band of the table was used as the group territory for making the story and for joint investigation of photos, and the remaining areas were used as personal territories for individual work. On the large table, G7 had sufficient space for shared visual separation of materials at the sides of the storyboard (see Figure 48(a)). However, on the small table (see Figure 48(b)) participants had limited space beside the storyboard and the middle of the table was mostly reserved for making the story on top of the storyboard. Personal territories were (almost) fully covered by photos, which meant that participants could not put their hands on the table and sit comfortably. Moreover, the limited area in the group territory did not let participants move the board to expand the group territory. This led to an increase in the probability of overlapping and piling when pairs manipulated the materials.

As shown in Figure 48(c) and Figure 48(d), in the *corner seating arrangement*, participants had the opportunity to separate photos on one side of the table (close to themselves) and move the story- board to the opposite side of the table to have more shared area to work together. Pairs had more problems on the small table during story-telling because they did not have enough space to comfortably work. Similar to the across seating arrangement on the small table, participants could not put their hands on the table to work comfortably. As Figure 48(c) and Figure 48(d) show, P23 rested his arm on the large table without covering any photos but on the small table, he couldn't do this without obstructing some photos.

As a result, story telling included more joint activity. In corner seating arrangement, pairs could put the storyboard far away from both participants and make more shared area with less overlap of materials. Therefore story-telling on the large table with the corner seating arrangement supported visual separation more and increased the quality of joint activities.

Travel planning: Materials provided were: four blank sheets of paper and 27 information sheets, 10 small (12.5x13.5cm), 16 medium (21x21cm), and 1 large (28x22cm), which contained text and images. These materials could fit on the large table without overlapping (see Figure 49(a) and Figure 49(c)) but they could not fit separately on the small table (see Figure 49(b) and Figure 49(d)).

Because of the large size of task materials in the travel-planning task, pairs necessarily needed more space for manipulating and sharing materials in comparison with the story-telling task. The statistical analysis in Chapter 4 supports this as it shows a significantly higher spatial usage in the travel-planning task. Statistical analysis also shows significantly more piling and above-the-table materials usage in the travel-planning task.

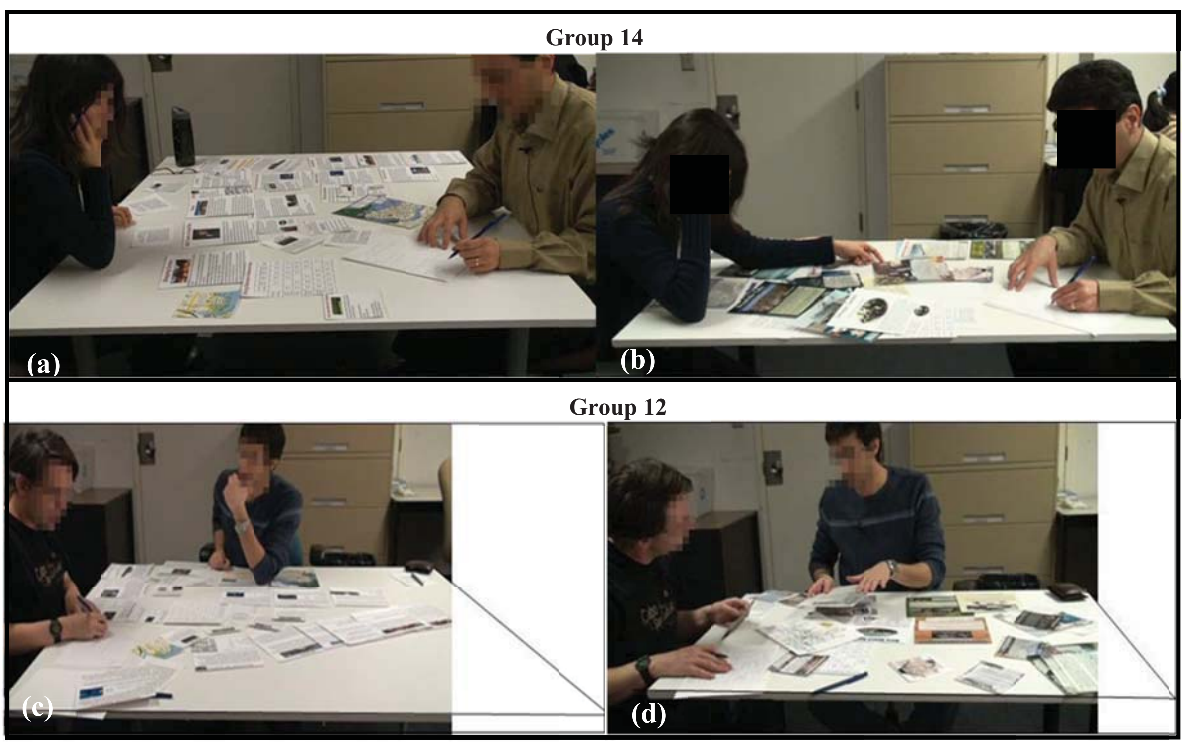


Figure 49: Travel-planning on large and small tables

Pairs applied more piling and above-the table materials usage to compensate for the space constraints in the travel-planning task, which led to limited visual separation (and likely workspace awareness, although statistical results do not confirm this[11]).

Pairs exhibited more individual activities in the travel-planning task. They had more requirements to consider, such as companions, available money, and demographics of the family for whom they were creating an itinerary. Materials had text that took time to read. Participants usually read information sheets and checked requirements and constraints individually. They then discussed the appropriate information sheets with their partner to see if they met the requirements and constraints. Usually, in this task, participants shared the information verbally without sharing the physical materials.

Unlike the story-telling task, in which laying out the photos in a meaningful order was part of the task activity, in the travel-planning task pairs had to write the itinerary on a piece of paper. However, as mentioned above four pairs (in five trials) created their itinerary by arranging information sheets on the table as a method for problem-solving. Having visual separation of materials and a draft of the itinerary was not easy for pairs on the small table, and this constraint decreased the quality of problem understanding. G11 was the only pair who sorted the information sheets for creating their itinerary on *both* table sizes; see Figure 50 and Figure 51.

In Figure 50, on the large table, G11 separated the plans for each day (inter-group visual separation) from each other, and information sheets within each day plan are visually separated (intra-group visual separation) as well. In Figure 51, although the plans for each day are separated from each other (inter-group visual separation), no intra-group separation within each day plan can be seen, and information sheets for one-day plan are overlapped. G11 did not have enough space for manipulating information sheets on the small table and mostly swapped them above the table.

[11] The coded workspace awareness incidents were based on incidents of participants' direct look at their partner's activities on the table. This only accounts for a limited amount of possible WA occurrences.

Figure 50: G11 laid out the itinerary on the large table

Figure 51: G11 laid out itinerary on the small table

This section, demonstrated that more space was needed for travel planning than for story telling to allow for parallel searching and cognitive tracing of the larger task materials. The smaller size and number of task materials in the story telling could easily be visually separated on both tables and pairs performed parallel searching and cognitive tracing on both. However, for travel planning, the small table was not large enough to spread task materials to enable parallel searching and cognitive tracing.

In the travel planning tasks pairs worked more individually. They needed more time to read the task materials, as the content of materials was largely textual. Moreover, three parts of the travel plan (three days' schedule) were independent of each other, and participants mostly divided these tasks activities between them and then combined them together. However, in the story-telling task, each photo in the story line was dependent on the next and previous ones, and thus, most of the time, participants did the task jointly.

5.4 Chapter Summary

This chapter has shown that the three independent factors in this study, table size, seating arrangement and task type, impacted external cognition behaviors of pairs. Table 12 shows different types of external cognition (presented in the first column of Table 12), the benefits gained from their use (presented in the second column of Table 12) and how the different independent factors impacted them (presented in the third column of Table 12) [12].

Table 12: External cognition behaviors and their benefits in current experimental study

External Cognition	***Benefits of external cognition***	***What increased the external cognition behaviors***
Grouping		
Piling	Decreasing memory load, compensating for the lack of space	Small table, corner seating arrangement, travel-planning
Visual-separation	External memory, individual cognition, group cognition, workspace awareness	Large table, across seating arrangement, story-telling
Cognitive Tracing		
Visual-separation	Externalizing the plane, Tracking the solution, individual and group cognition	Large table, Across seating arrangement, story-telling

[12] Table 12 was filled based on qualitative analysis

The first part of this chapter discussed how pairs benefitted from external cognition on the large table and how lack of space on the small table limited those benefits of external cognition. The more available space pairs had, the more task materials they could fit separately (visual separation) on the table. Visual separation (in both types of external cognition, *grouping* and *cognitive tracing*) had a positive impact on individual and group cognition of pairs while completing tasks. Task materials, which were visually available on the table, aided parallel searching among materials and acted as external memories for participants by eliminating the need to remember the contents of task materials. Moreover, by having visual separation the probability of workspace awareness was increased because participants could see what kind of activity their partner was doing and which task materials he/she was working with. However, the small table forced pairs to stack task materials in piles and use above-the-table space to manipulate materials to cope with the lack of space.

The second half of this chapter argued that table size was not the only factor which affected the external cognition behaviors of participants in the study. External cognition was influenced by pairs' seating arrangement and the type of task that they did on the tables.

In the corner seating arrangement some portions of the table were not accessible for one or both participants, specifically in the large table. This constraint limited the area of their activities, decreased the number of separated materials on the table and increased above-the-table material usage. Because participants sat on different sides of tables in the corner seating arrangement and shared part of their personal territories, they had less space for individual work in comparison with the across seating arrangement. However, pairs could share more area with each other in the corner seating arrangement, which was helpful for tasks with more joint activities.

The problem-solving strategies used in the two tasks differed. To make their story, pairs had to sort the photos, so cognitive tracing was part of their problem-solving. Conversely, to make the itinerary, cognitive tracing was a potential problem-solving strategy but only a few pairs used that method. The small size and number of task materials in the story telling allowed cognitive tracing of ordered photos. However, even on the large table, visual separation and cognitive tracing were not easy for pairs when travel-planning.

The collaboration strategies in the two tasks were also different. In story telling, participants worked jointly because each step of the solution making process completely depended on the previous and next steps, as the story should be a meaningful flow of photos. However, travel planning included three independent activities (because of the requirement for a three day schedule), so most pairs preferred to divide the task activities between each other before combining the results. This strategy of working, mixed-focused collaboration [57] in the story-telling task resulted in increased use of personal territories.

The next chapter will discuss the similarities and differences of conventional and digital tables in the case of external opportunities. Moreover, the finding of this research will be compared with the similar findings from other research. Based on these discussions, design implications will be provided for designers of digital tabletops.

Chapter 6
Discussion

This work investigated the effects of table size on participants' behaviors during two collaborative problem-solving tasks. The results revealed that providing a sufficiently large space for collaborative tabletop problem solving supports external cognition. However, the seating arrangement and task type are contributing factors that also influence that amount of space on the table that is available for cognitive off-loading of information.

In this chapter, the results presented in Chapters 4 and 5 are discussed. First, the importance of table size is discussed, and then space limitations caused by different factors are analyzed on both table sizes. Finally, a discussion of potential and existing solutions for compensating for such space limitations is provided.

6.1 Importance of Table Size

The findings presented in the previous chapters show the significant effect of table size on the external cognition behavior of participants. The question of "Why is table size important in collaborative problem-solving tasks?" is revisited in this section to discuss whether the results from the experiment are consistent with previous findings in the literature.

6.1.1 More space can accommodate distribution of task materials

This research and research from the literature show that people have a tendency to use large areas of a given table surface to distribute task materials, when such space is provided. In their tabletop territoriality research on traditional tables, Scott and Carpendale [49] observed that people increased the size of storage territories by spreading the artifacts to facilitate searching among them. Everitt et al. [13] also reported that collaborators liked to maximize documents to fill a digital table, although they found this to be a disadvantage. In their case, they explored the problem of overlapping documents on a shared digital tabletop, which introduced conflicts between people who were in different stages of their taskwork. However, the digital table they studied was relatively small (107cm diagonal) compared to the tables used in this thesis research (small table: 145.96cm diagonal; large table: 198.1cm diagonal). Thus, it is unclear whether this problem would occur (at least to the same extent) on a larger digital table.

As reported in Section 4.1.2 all pairs of participants in my study distributed task materials more widely on the large table than on the small table. Moreover, participants also used more of the available table space on the large table than on the small table.

6.1.2 Space affects external cognition behaviors in various stages of problem solving

Having more space to distribute artifacts resulted in the use of more external cognition on the large table. As reported in Chapter 5, having more visible materials distributed on the table enabled participants to look at more than one item at once, which facilitates parallel searching through the items. The parallel searching provides external memory for people, and consequently aids external cognition as noted by Sharp et al. [52].

The study presented in this research revealed that in each stage of problem solving collaborators distributed materials in different ways. This observation indicates how users externalize their cognition to support a task's needs at each stage. Different representations are helpful for better *understanding* of the problem, *organizing* task materials and eventually *solution making* for the problem. As the distribution structure of materials changes, perception of these materials and the entire workspace can change accordingly, facilitating each of the different stages more effectively [1].

Problem understanding: As discussed in Chapter 2, De Bruijn and Spence [6] introduced the notion of opportunistic browsing to describe people unintentionally browsing through information to understand possible options that might spark ideas when problem solving. The results of this research support this idea by showing that most pairs spread task materials at the beginning of the task in an ad hoc structure. Browsing visible items on the table appeared to help participants identify potential connections between these items, facilitated by simultaneous access to information. Comparisons could then easily be done visually rather than relying on their memory.

As Andrew et al.'s [1] studies on sense making have shown, a glance or turn of the head is enough to grab a piece of information and return to the current task. Thus, the ability to visually separate and distribute materials given a large table size can facilitate such information assessment to understand what information is available for the problem at hand.

Organizing task materials: The findings reveal that as understanding evolves the organization of materials is developed by creating categories of related materials. People used the additional space on the large table to put multiple objects beside each other and separate those from other categories. Kirsh [29] referred to this benefit of space as a *semantic layer* that provides meaning to the visible information.

Andrews et al. [1] claimed that proximity of materials helps to refresh internal memory. Their studies also showed that people place important documents in the focal point of the workspace with full visibility while less important documents were piled up. Similar behaviors were seen in this study. The potential task materials were visually separated to be easily seen in the attention focal point of the tables in the personal or group territories. However, the impoverished environment of the small table forced users to overlap or pile some materials to overcome space limitations.

Solution making: Distribution and categorization of materials are not the only ways to externalize cognition. The advantage of using space helps people think about their problem via cognitive tracing. The internal model of the (rough) solution can be externalized and explored by structuring and restructuring objects on the table chronologically, or in some other task-appropriate manner. The flexibility served by the large table supported examining the developing solution. The study showed that the solution can evolve on the tabletop workspace by changing the existing structure of materials via ordering, arranging, and alignment.

6.2 Other Factors that Affect External Cognition in a Tabletop Workspace

The most important finding from the user study is that the table size is not the only factor affecting people's external cognition behavior during collaborative tabletop work. As reported in Chapters 4 and 5, having a larger table does not necessarily guarantee that participants have effective access to the additional workspace it provides. Based on the study findings, the following factors should also be considered when determining what table size is needed in a given usage context.

Task type: The table surface may be sufficient for one task but limited for another task. An important aspect of a problem-solving task is the kind of search that is required. Parallel search and browsing need more space to spread out the artifacts and review them, while sequential search can be accomplished using a pile of artifacts. Furthermore, it is important to consider how much individual or collaborative work is involved in a task. In the story-telling task, participants started working mostly collaboratively when creating the story line on the storyboard. The findings revealed that when there was less space, participants moved some of their personal work above the table by holding artifacts in their hands. To better facilitate this personal work, a digital tabletop system should be designed to better support the way people work in the group territory. On the other hand, in the travel-planning task, the collaboration started later. Therefore, personal territories occupied most of the table surface. The findings revealed similar above-the-table searching when there was limited tabletop workspace when people were working individually. Thus, a digital tabletop system should better support management and exploration of workspace items in the personal territory for tasks that involve such parallel work needs.

Number and size of artifacts: For the same task, if the number and size of artifacts change, the table surface may be insufficient for participants. In the travel-planning task, because the task materials (i.e., information sheets, maps) were larger than the photo slides provided in the story-telling task, participants were more restricted when organizing them on the table. On the other hand, sorting and organizing the smaller photo slides on the table surface in the story-telling task was much easier. Digital tabletop systems need to have flexibility to deal with artifacts of different amounts and sizes. Of course, supporting an unlimited capacity may not be possible, for instance, even if external devices are used to expand the workspace (see Section 6.3.1 below) there will likely still be limitations. However, providing a system design and system tools that provide greater flexibility for spatial manipulation and management of task materials would facilitate the use of external cognition, across a wider variety of tasks and task contexts, than traditional tables.

Seating arrangement: The study findings revealed that when users sit closer together at a table (i.e., the corner seating arrangement), some parts of the table surface might be inaccessible to them. Users can use those areas for discarded items, but searching through artifacts stored there is not easy. A digital tabletop system design should be flexible by considering the seating arrangement to make the most beneficial use of the table surface.

Number of users: A given table can be large enough for two people, but may be insufficient for four people. Most tabletop workspaces will have a saturation point for its capacity to support a given number of people, for a given task, task materials, user arrangement, etc. However, some changes may be applied to accommodate more people. A simple example is that a lunch table that is large enough to hold the meal trays for two or three people may feel crowded when additional people join in. However, it may become sufficient if people remove their trays and only have their plates on the table, creating additional space (and with smaller "task materials"). Or, the table may become sufficiently large when an expandable leaf is added to accommodate the extra people and their meal trays.

Expected user population: Users may be children, seniors, or they may have a certain physical disability or unusual physical characteristics (arm length or height). In such cases, the physical aspects of the table should be designed appropriately for these expected users.

6.3 Managing Space in the Table Workspace

Generally, people may prefer to have a large table for doing their tasks, even if they do not use the entire space. The findings of this research have shown that participants used the large space to avoid piling artifacts or holding them in their hands, although sometimes, depending on their seating arrangement, some parts of the table were inaccessible (or not easily accessible).

However, large tables are often expensive, not easy to move, take a large space in the working environment, and unnecessary when the provided space is not required for the given tasks and users. Therefore, it makes sense to think about what a reasonable table size would be for a specific task type. But even if an affordable and sufficient table size can be roughly estimated for a task, there may not be sufficient space for all situations. Moreover, there may be cases when the table is too large and users may not be able to access the entire space. In these cases, the design of a digital tabletop system should provide additional solutions to enable users to deal with space concerns. This section addresses such solutions, considering both space availability and accessibility in tabletop workspaces.

6.3.1 Expanding the Tabletop Workspace

In case of space limitations in personal or group territories, people can use two different techniques to gain more space. One is hardware-based by using external devices to provide more pixels, and the other one is software-based by scaling artifacts.

6.3.1.1 Gaining Space using External Devices

One approach to dealing with the space limitations in a tabletop workspace is to expand the available workspace using additional surfaces. To expand a digital tabletop workspace, for example, would be possible with the aid of such devices as a nearby wall display or a mobile handheld computer (e.g., a tablet or smartphone). This solution can be useful for both individual and collaborative work by providing mechanisms to expand the personal and group territories.

Expanding personal territories: Each person may transfer artifacts from his/her personal territory on a digital table to a nearby mobile device to be used and then perhaps moved back to the digital table at a later time. For instance, an iPad™ tablet could be used to view or manipulate a pile of digital documents when there is no space available to add another pile to a digital tabletop workspace, or when artifacts are needed often and should not be minimized on the digital tabletop workspace. Chang and Li's Deep Shot technique [4], developed for moving items between a personal computer (PC) and a smartphone, could for example, be adapted to enable similar table-to-tablet object transfers. The Deep Shot system can be used to transfer an address specified in a Google map on a PC to a Google map on the smartphone by taking a photo with the smartphone's camera of the PC's screen (displaying the Google map location) and automatically extracting the appropriate geospatial information.

Designers at Microsoft Surface[13] implemented a similarly lightweight way to transfer artifacts between mobile phones and a digital table. The Microsoft Surface's capabilities focus on document and photo dumping from mobile devices onto the digital table. The Elope [34] and Interactive Spaces [26] systems provided similar designs to connect mobile devices to large, interactive workspaces, in order to provide expanded workspaces. The Elope system allowed connecting unknown mobile devices to large displays without initial set up, and Interactive Spaces provided a multi-display workspace. These three systems were primarily designed to enable sharing of objects from personal, mobile displays onto shared, large workspaces, but the general design concept may be used in the reverse order to facilitate the expansion of personal territories from an insufficient shared workspace. Thus, artifacts could be transferred from a personal territory on the digital table to an external mobile device to compensate for space limitations.

UbiTable [53] used a digital table as a shared, temporary display for impromptu interaction based on artifacts originating on personal portable devices. The UbiTable system provided each user with a separated private space on their mobile device (e.g. a laptop), and both a personal (i.e. semi-private) space and a shared public space on the digital table for individual and collaborative work on the tabletop. In the private space, artifacts were not visible and accessible to other users, while in the personal space they were visible but not accessible (i.e., only the "owner" of that space could manipulate any contained artifacts). To expand someone's personal territory, semi-private artifacts could be moved back and forth between the table and mobile device. This provided both additional personal workspace to address space limitations on the digital table, as well as a greater level of privacy for individual work (an issue not explored in this research).

Expanding the group territory: If people have insufficient space in the group territory, they can also create extra space for collaborative work by expanding the workspace onto nearby external devices. For example, one of the earliest systems to take advantage of multi-device integration was Rekimoto and Saitoh's Augmented Surfaces system [38] (see Figure 52), in which artifacts could be moved between laptops, a wall display, and a digital table. Rekimoto and Satoh also developed a mechanism to link physical objects (e.g. a video tape) to digital artifacts in this environment.

[13] http://www.microsoft.com/surface

Figure 52. The Augmented Surfaces multi-device environment (from [38])[14]

More recently, Jiang et al. implemented the WeSpace system [25], a multi-device system consisting primarily of a digital table and a large digital wall that enabled users to connect other digital devices (e.g. laptops) as auxiliary workspaces. This system configuration would be useful for space management within the group territory, as it extended to the connected wall display. It would also be useful for comprehension and discussion of shared artifacts placed in this extended group territory, as artifacts displayed on the wall display could be viewed at the same orientation by all users (unlike shared artifacts displayed on the table, which may appear at different orientations for different users, depending on the user arrangement). Both may increase the use and benefit of external cognition, though this issue warrants further investigation. Interactive Spaces [26] provided a similar digital table plus digital wall configuration, enabling similar expansion of group territory across connected surfaces.

Everitt et al. [13] studied the behavior of collaborators in a similar multi-device environment (Figure 53). In their study, teaching assistants used a digital table and nearby wall display to work with course materials. They reported that participants tended to use materials on both the table and wall displays, but tended to use them each for different purposes.. In particular, the TAs tended to use the table for organizing documents and the wall for comparing documents. Participants reported that they liked the wall display for discussion because it had the same orientation for everyone.

[14] Reprinted by permission under license 2894861220112, purchased from Association for Computing Machinery, Inc. April 2012.

Figure 53. Collaborators working on a digital table connected with a wall display (from [13])[15]

Figure 54 illustrates a similar workspace configuration for a commercial conference table, designed by the SteelCase Company[16]. In this design solution, each person has a mobile device to serve as their personal territory and two connected wall displays to serve as two group territories. This design concept could be extended to include a digital table augmented with sidewall displays. This would provide the group with several options for working with shared artifacts and for using various external cognition mechanisms to facilitate various task phases, such as problem understanding, organizing and solution making.

Figure 54. A conference table, designed by SteelCase, lets people connect laptops and mobile devices, and share two large wall displays for group work.[17]

[15] Reused by permission of Mitsubishi Electric Research Laboratories, Inc (MERL), 2005. 201 Broadway, Cambridge, Massachusetts 02139

[16] http://www.steelcase.eu/

[17] http://www.technologyreview.com/business/38407/ (accessed January 2012). The permission granted by Wright's Media for reprinting the image in this thesis (Jennifer Martin, Licensing & Content Manager).

6.3.1.2 Gaining Space using Scaling

As discussed in the Chapter 5, on a large table people often want to have artifacts closer to read or see them better. On conventional tables people cannot rescale artifacts, so they pick them up, hold them above the table, and look at them closer. However, on a digital table artifacts can be rescaled. Therefore, it is possible to minimize (or iconize) those artifacts that are not necessary at the moment and enlarge essential artifacts. Rescaling can be manually controlled by users or can be automatically performed by the system. Automatic scaling can be achieved, for example, by using a mobile interface tool, such as a local magnifier tool, that can be dragged over artifacts to temporarily expand them to some extent (similar to the magnifying effect in the Mac OS X dock) for better browsing (e.g., [24]. This feature is useful for opportunistic browsing. Scaling is one of the common solutions suggested for space management in interactive systems. Automatic scaling can also be location-based, for example, the Scalable Fabric system [40], designed for desktop displays, scaled down task windows when they were placed close to the edge of the display. This technique enabled users to work normally with windows in a central work area, and then easily switch to other tasks by finding them in the marginal area.

A notable point is that enlarging an artifact may cover other users' artifacts, which could be disturbing particularly in the group territory. Zooming in/out a part of an artifact, as a special type of scaling, is useful to avoid overlapping other items on the table. Sanneblad and Holmquist [44] utilized a similar technique on a video wall, called Ubiquitous Graphics, to zoom in parts of a large map in order to see more details or to annotate items.

6.3.2 Improving Accessibility to Artifacts in a Digital Tabletop Workspace

People are limited by their physical capabilities. If they sit around the table, they can only physically access tabletop materials within arms-length distance without expending further effort such as standing up and walking around the table. Therefore, some tabletop artifacts, or some areas of the workspace, may not be easily accessible to collaborators. Various solutions have been proposed to resolve this problem, as discussed below.

6.3.2.1 **Virtually Extending User's Reach Across the Workspace**

One approach for improving the accessibility of artifacts across a digital tabletop workspace is to provide a mechanism to virtually extend the user's reach across the workspace. Pinelle et al. [35] used virtual embodiments (e.g., virtual arms) to enable users to access artifacts out of their physical arm's reach. A virtual embodiment is like a virtual arm extension by which users can perform the same functions they can do with their hands, including moving around artifacts, rescaling, zooming and other artifact manipulations. On a conventional table without any digital technologies this is not easily possible. Another approach is to use an external device for manipulating or viewing artifacts (especially out-of-reach ones). This is similar to the Pebbles system [32] that enabled users to control artifacts and applications on devices (e.g., a PC) with their handheld devices. A navigation panel, which was a sort of bird's-eye view, could be displayed on the mobile device and users could zoom in or out on each area, point to and move around artifacts. Advantages of this approach are that is does not take space for the navigation panel from the table surface and provides less intrusion into other users' work (e.g. no shadow over other artifacts).

6.3.2.2 **Automating Artifact Movement from Remote Workspace Locations**

Another approach to helping users access artifacts outside their physical reach on the table is to automatically move artifacts closer to the user. One such technique is to use an Interface Current, proposed by Hinrichs et al. [19], which provided a user-controllable automatic flow that circulates artifacts around the table inside of an interface container. This technique allowed items located in the Interface Current to circulate in front of each user at the table. For example, an Interface Current could be used as a moving band along the table edge similar to a conveyer belt. Besides the dynamic flow of artifacts, Interface Currents could magnify items when they are adjacent to users. This automatic scaling feature is useful for opportunistic browsing, as discussed above. Therefore, the Interface Currents essentially combined automatic movement and scaling in a manner that helped users manage artifacts in a tabletop workspace. Hinrichs et al. [19] also showed that Interface Currents are useful for information sharing in collaborative tabletop activities.

6.4 Summary

This chapter discussed the various size-related factors that impact the use of external cognition on a collaborative tabletop workspace, and how these factors can be considered in the design of a digital table to better facilitate external cognition when space limitations exist. The available space for working on any given table depends on a variety of factors, beyond the obvious factor of table size. In particular, the findings of this research show that seating arrangement of people at the table and the task type also significantly impact the use of external cognition during collaborative problem solving tasks. Beyond identifying these specific factors, it is important understand how these factors impact external cognition and collaboration, to extrapolate their implications. To this end, this chapter discussed additional design considerations that may influence the availability or accessibility of a given workspace, and in turn, affect the ability for collaborators to use external cognition to facilitate their problem solving activities. For instance, the table size limits the number or size of artifacts that can be accommodated, and different user populations (e.g. age or physical ability) will have different physical capabilities, and thus, impact how much of a given workspace they can physically access. Therefore, understanding the expected usage context, including the likely tasks and users, is important for providing an appropriate tabletop workspace.

On the surface, it may seem that providing the biggest possible table with a highly mobile user arrangement would provide the best environment for using external cognition during collaborative problem solving activities. However, practically speaking, this solution is often not possible, or not preferable. First, a large table necessitates having a large physical area available in the working environment; thus, spatial constraints of the environment may lead to selecting a smaller table. Second, the primary task or users of the table may not require a large table, and, thus, selecting a large table to accommodate the occasional need for more workspace may not be financially or practically feasible, and may seem out of place in an environment equipped with much smaller furniture (e.g., a children's playroom). Thus, choosing a table size solution that works for the primary usage context makes the most practical sense. Moreover, the study findings revealed that although a larger tabletop workspace provides more opportunities to use external cognition to facilitate the problem solving process, collaborators were able to adopt alternative coping strategies when space was limited.

Unlike the traditional tabletop workspaces studied in this research, where the tabletop workspace and the available task materials are fixed in size, digital tabletop workspaces lift some of the constraints of the physical world when it comes to scaling or interacting with task artifacts. Such capabilities provide the potential to offer collaborators additional strategies for coping with space limitations in the tabletop workspace. This chapter discussed two workspace-related challenges that may be addressed using digital tabletop workspace, and identified several existing technological solutions that may help address these challenges. In particular, the issues of space availability (i.e. when a tabletop does not provide sufficient space), and of accessibility of the workspace (i.e. when one or more collaborator cannot physically reach an area of the workspace), were identified as challenges observed in this research that may be addressed by a digital tabletop system. The availability challenge may be addressed by: 1) expanding a digital tabletop workspace using a multi-device solution involving connected peripheral displays, either mobile, personal displays or large, shared displays, depending on the task needs, or 2) using interface or interaction techniques that rely on scaling the workspace or artifacts to provide either expanded screen real estate, or to make more effective use of the available workspace. The accessibility challenge may be addressed by using interaction techniques on a digital tabletop workspace (or across a multi-device workspace) that: 1) virtually extend the user's reach across the workspace, or 2) use automation to move distant objects closer to the user.

Chapter 7
Conclusions

This thesis investigated the impact of a table's physical features on human collaborative work within a tabletop workspace. Specifically, table size and seating arrangement effects were studied in an observational study. The collected observations were then qualitatively and quantitatively analyzed to determine how the specific physical features and group settings impacted the use of external cognition during different collaborative problem-solving tasks. This chapter reviews the targeted research objectives, contributions, and future work. The results of this research contribute to the foundational knowledge in the HCI and CSCW communities on external cognition behavior in a shared tabletop workspace, as well as practical knowledge on the design of digital tabletop workspaces that facilitate such external cognition behavior.

7.1 Research Objectives

The main goal of this research was to explore the effect of table size on external cognition while people were working collaboratively on a table. The work was completed based on tasks using paper-based artifacts, and explored how individuals manipulate these artifacts to study what factors facilitate or hinder their individual and collaborative work. To address this goal, four objectives were investigated:

Objective 1. Design a suitable testing environment to identify factors influenced by the size of table workspace.

Objective 2. Investigate the effect of identified factors on external cognition.

Objective 3. Develop recommendations for compensating size limitations in the tabletop workspace based on findings.

These objectives were attained through observing two collaborative tasks, storytelling and travel planning, on two sizes of traditional tables and analyzing the obtained results. Although the initial goal was to study the effect of table size, during pilot studies seating arrangement and artifact size for different tasks were also determined to be important, and therefore taken into account in the final empirical study. The findings provided insights on how the physical characteristics of a table could facilitate or limit users' activities in tabletop personal and group territories. The results supported the initial hypothesis that the size of a table can significantly affect tabletop collaboration, and in particular, collaborators' use of external cognition during problem solving tasks at a table.

7.2 Contributions

This research primarily aimed to investigate one physical characteristic of a tabletop workspace, table size, and its relation to cognitive ergonomics of users. In addition, this thesis considered two different factors of co-located, collaborative problem solving, task types and seating arrangement of users. As a result, challenges related to the availability and accessibility of space on a table were identified. Moreover, the conducted study provided insights on potential implications for the design of digital tabletop systems. In particular, this thesis discussed existing design solutions and extensions of existing solutions that have the potential to address the space availability and accessibility challenges identified by this research The following sections summarize these contributions.

7.2.1 Investigation of linkages between table size, seating arrangement, task type and external cognition in tabletop collaboration

This research was first motivated by the work of Ryall et al. [43] (discussed in Section 2.1.4). I leveraged their work by applying key changes to the experimental design. These changes included the use of two different tasks that utilized different sizes of materials, the inclusion of different seating arrangements, the use of different table sizes (one that was similar to the tables used in Ryall et al.'s study and one that was significantly larger), and traditional tables instead of digital tables (as used in Ryall et al.'s study). The surface area of one table in this research was twice the size of the other. Furthermore, one task included small pieces of materials and the other included larger ones, to the extent where all of the larger pieces could not fit easily on the table's surface. This research studied two seating arrangements of participants: across from one another and at the sides of one corner of each table. All of these changes were designed to better investigate whether other factors related to table size and space availability can influence collaborative problem solving on a table.

Moreover, this thesis is the first investigation of the effects of such physical factors on people's use of external cognition during tabletop collaboration. It studied the way people in tabletop activities externalize their thinking and behaviors by managing and playing with materials on the workspace to figure out the relationship between external cognition and the table size. In particular, it focused on piling, visual separation and cognitive tracing as key tenets of external cognition.

7.2.2 Identification of space management strategies that enable individual and group external cognition behaviors in tabletop collaborative problem solving

Previous research efforts analyzed collaborative tabletop interaction behaviors in personal and group territories [51]. This thesis investigated how people manage the table space in these territories by analyzing their external cognition behaviors during problem-solving tasks. The task type and seating arrangement have implicit impact on the development of personal and group territories and this in turn, impacts the availability of these personal and group territories to support external cognition behavior.

In the storytelling task, participants tended to work together in the group territory, while in travel planning individual work was more prominent in the personal territories. Furthermore, seating arrangement affects the location and size of personal and group territories. When users were in the corner seating arrangement, they shared the table corner as a group territory. The group territory in this arrangement is more beneficial for external cognition. Users are close together and materials could be placed in the same orientation for both, allowing them to reap more benefit from workspace awareness.

7.2.3 Identification of potential design solutions for space management and accessibility in personal and group territories in digital tabletop workspaces

Any given table might not provide sufficient space for unplanned tasks or unexpected users. Even for a specific preplanned task, the table space might not be sufficient in some cases. For example, assume a crime scene investigation team uses a table to collaboratively analyze evidence gathered from a crime scene. It is often impossible, or impractical, to imagine that the table might be able to accommodate every type or size of evidence materials that the team may need to analyze in all of their possible cases. Thus, sometimes the team would need to compromise and use alternative strategies for their analyses.

Since the ultimate goal of this research is to improve the design of digital tabletops, the study findings were analyzed for potential design solutions to assist with space management and accessibility on such digital tables. Multi-device workspaces, such as a digital tabletop connected to laptop or tablet displays, were identified as a potential design solution to provide additional space for personal or group territories, especially when a tabletop interface does not provide sufficient space for a given task. For expanding personal territories, a mobile device may be used, while for expanding the group territory, a video wall or nearby large-screen television may be more appropriate. Another possible solution is scaling artifacts to have room for more important information at each moment. Scaling can be done manually by users, or automatically based on where users are touching the table or how close are artifacts to the center of the table.

When a digital tabletop workspace provides excessive space, or due to seating arrangements some areas of the workspace become difficult to reach, accessibility to content can hinder effective use of the workspace. Digital tabletop design solutions that introduce automated object movement, such as interface currents [19], or techniques that employ virtual reach extensions, such as virtual embodiments [35], were identified as potential design solutions that address accessibility concerns. Such solutions, for instance, could be employed when children wish to play on a digital table designed for adults.

7.3 Future Work

The experimental design used in this research can be extended to investigate further workspace characteristics in tabletop collaborative problem solving. In particular, a more extensive analysis of interaction between physical characteristics, such as artifact size and table shape, and external cognition could be considered. The following sections elaborate on potential extensions of this research.

7.3.1 Investigating additional factors that may influence the spatial use of a collaborative tabletop workspace

As all possible factors impacting the use of tabletop workspace could not be investigated in this research, additional work is warranted to scrutinize additional factors that may also influence the use of space and external cognition behavior in tabletop collaboration. Such follow-up work could include tables of the same size used in this research to enable collection of comparable data, which consequently would be helpful for further insights related to the design of digital tables. Potential directions to proceed with this research are as follows.

- *Investigating the impact of group size*: Another important design factor that could be investigated is the group size as this research considered only a pair of participants working collaboratively on a table. Space management and external cognitive behaviors seem to be different in various group sizes. Ryall et al. [43] reported that different group sizes lead to different strategies in collaborative tabletop problem solving. It would be interesting to observe the group size effect in the experimental setting used in this thesis.

- *Investigating the impact of age, population and cultural factors*: Future studies could also include different user populations to better understand the generalizability of the results from this study. For example, people of different ages (e.g. children or elderly), people with different physical disabilities, and people of different nationalities could be included, as previous work has suggested that such demographic factors may influence people's spatial use of the table [59].

- *Investigating tasks with measurable outcomes*: The tasks included in the study described in this thesis were open-ended problem-solving tasks. Other tasks with more easily evaluable outcomes or measurable aspects could be investigated to enable the outcome quality of the collaborative task or the completion time to be evaluated in more detail. This would enable, for instance, the ability to assess the effect of limited table space on product quality and performance of participants.

7.3.2 Replicating the investigation on digital tables

Another research direction that warrants investigation is to replicate the conducted experiment on a digital tabletop platform. Two similar tables, of sizes comparable to the tabletop workspaces used in this thesis, or one large digital table could be used, where the "small" tabletop size could be emulated by activating only a subset (e.g., half) of the tabletop interface. In this study, the width of the large table equaled the length of small table, thus this approach would provide comparable results, especially if participants are given a fixed seating configuration.

Even if experiments with two table sizes cannot be replicated on a given digital table platform, a study investigating the spatial management and accessibility strategies on a digital tabletop platform would clarify the generalizability of the findings of this thesis to digital tabletop workspaces, as well as potentially identify additional strategies used to interact with digital media. Though some previous studies have investigated spatial use of artifacts on a digital tabletop (e.g., [43] and [49]), none have investigated the impact of workspace use and its interaction with external cognition.

Appendix A
Recruiting Participants

Department of Systems Design Engineering
University of Waterloo

PARTICIPANTS NEEDED FOR
RESEARCH ON
COLLABORATION IN SHARED WORKSPACES

We are looking for volunteers to take part in a study of collaborative tabletop interaction.

As a participant in this study, you would be asked to:

- Perform two trials of one type of collaborative task (story telling or travel planning) at different sized tabletop workspaces.
- Perform two trials of the other type of collaborative task, again at different sized tabletop workspaces.
- Participate in a brief interview.

Your participation, with a partner, would involve 2 sessions, each of which is approximately 30 minutes (total 1 hour).

In appreciation for your time, you will receive up to **$20.**

The study will be held between Feb3 and feb20, 2009.

For more information about this study, or to volunteer for this study, please contact:

Sepinood H.Gashti
Department of Systems Design Engineering
at
519-888-4567 Ext. 36813
Email: shajizad@uwaterloo.ca

This study has been reviewed by, and received ethics clearance through, the Office of Research Ethics, University of Waterloo.

Recruiting EMAIL

Subject: Participate in a Research Study

Message Body:

We are seeking participants for a study investigating collaborative tabletop interaction. Participants will be asked to:

Perform two trials of one type of collaborative task (story telling or travel planning) at different sized tabletop workspaces.

Perform two trials of the other type of collaborative task, again at different sized tabletop workspaces.

Participate in a brief interview.

Your participation, with a partner, would involve 4 sessions, each of which is approximately 20 minutes. The study will be video taped.

In appreciation for your time, you will receive $20 for completing all four sessions.

The study will be held between Feb3 and feb20, 2009.

Please contact Sepinood H.Gashti (email: shajizad@uwaterloo.ca, phone 519-888-4567 Ext. 36813), Department of Systems Design Engineering, University of Waterloo.

This study has been reviewed by, and received ethics clearance through, the Office of Research Ethics, University of Waterloo.

Appendix B

Task Instructions

Task instruction sheet for Story-telling task (Friends series)

Please make a story with pictures of Friends series provided for you. You can choose one from following themes for your story: Friendship, Family, Roommate, Dating and Entertainment.

If you want, you can make your story lines on the board.

You have 20 minutes for this task.

Task instruction sheet for Story-telling task (Seinfeld series)

Please make a story with pictures of Seinfeld series provided for you. You can choose one from following themes for your story: Friendship, Family, Roommate, Dating and Entertainment.

If you want, you can make your story lines on the board.

You have 20 minutes for this task.

Task instruction for travel-planning task (Calgary)

You are going to plan a trip for a family (parents with two children, a 13-year old son and an 18-year old daughter). They intend to go to Calgary in July for a weekend, from Friday morning to Sunday dinner time. They have prepaid for a hotel located in downtown. They have also rented a van (prepaid and unlimited miles). They have dedicated $800 for sightseeing and food (this budget excludes rental car, and gas expenses).

Your task is to plan an appropriate itinerary for three days and two evenings using the materials provided for you. Don't worry about accommodation, car rental and gas fees.

Task instruction for travel-planning task (Vancouver)

You are going to plan a trip for a family (Parents and two children, a 13-year old son and an 18-year old daughter). They intend to go to Vancouver in July for a weekend, from Friday morning to Sunday dinner time. They have prepaid for a hotel located in downtown. They have also rented a van (prepaid and unlimited miles). They have dedicated $800 for sightseeing and food (this budget excludes rental car, and gas expenses).

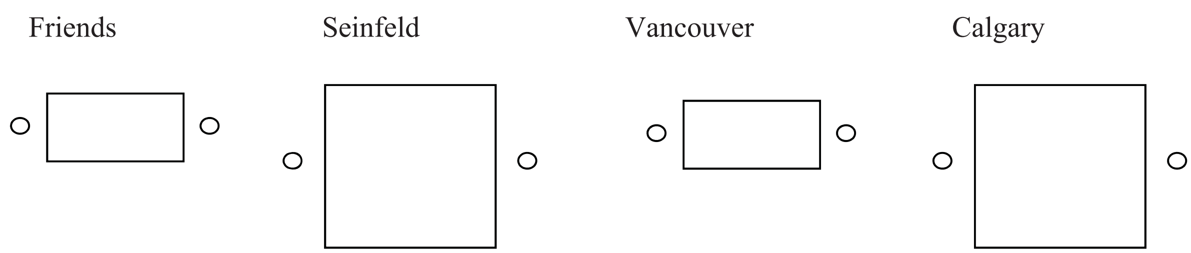
Your task is to plan an appropriate itinerary for three days and two evenings using the materials provided for you. Don't worry about accommodation, car rental and gas fees.

Appendix C

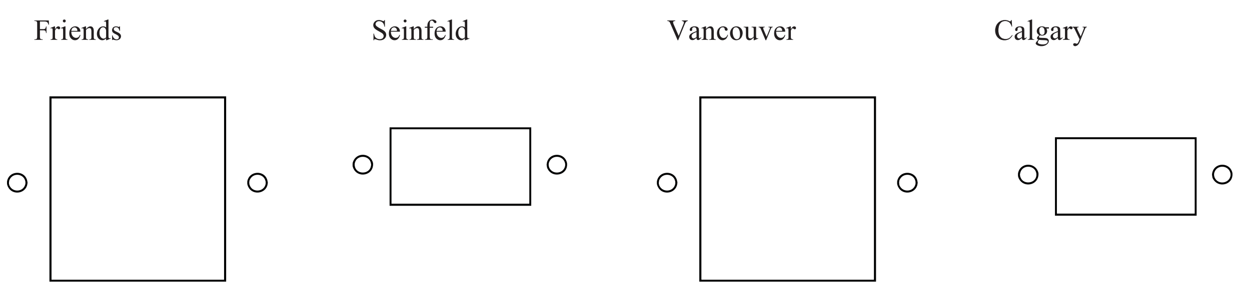
Experimental Design

For each layout, two experiments was run.

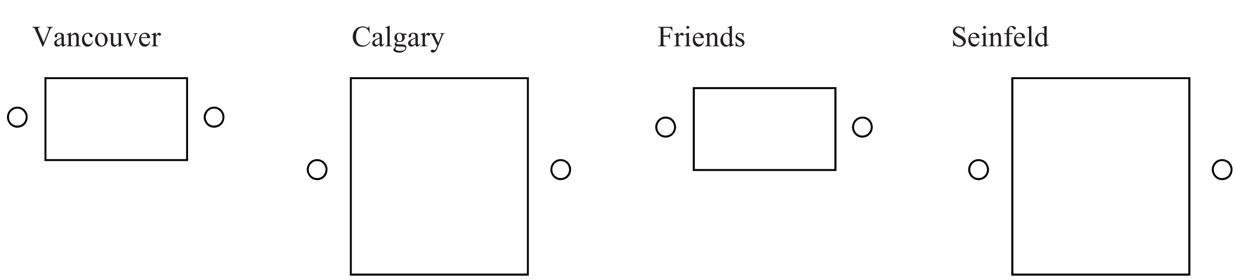
G2 & G13:



G3 & G14:

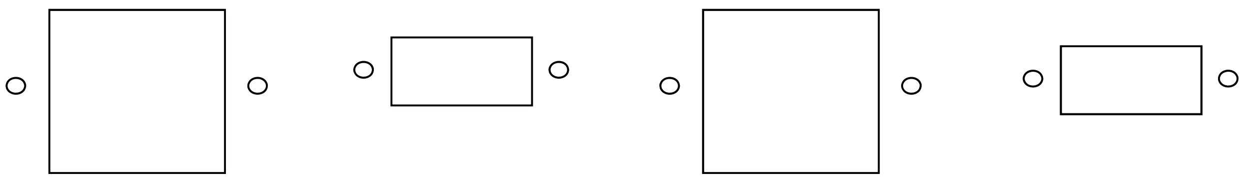


G6 & G8:



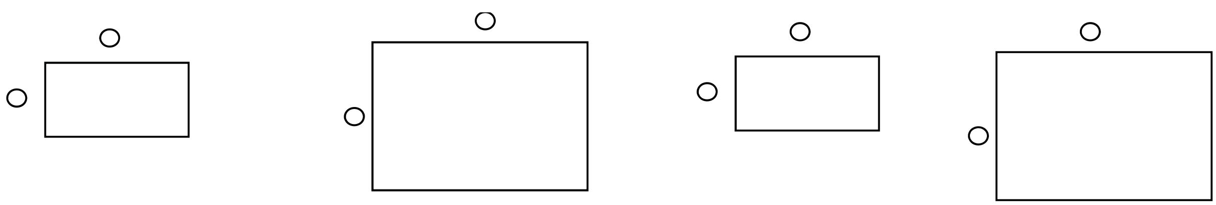
G7 & G15:

Vancouver Calgary Friends Seinfeld



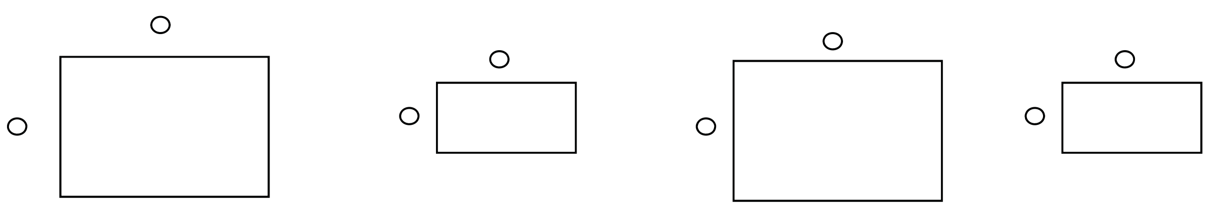
G9 & G16:

Friends Seinfeld Vancouver Calgary



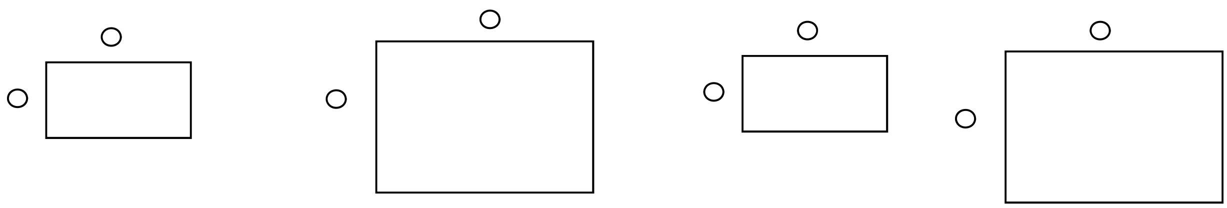
G10 & G17:

Friends Seinfeld Vancouver Calgary



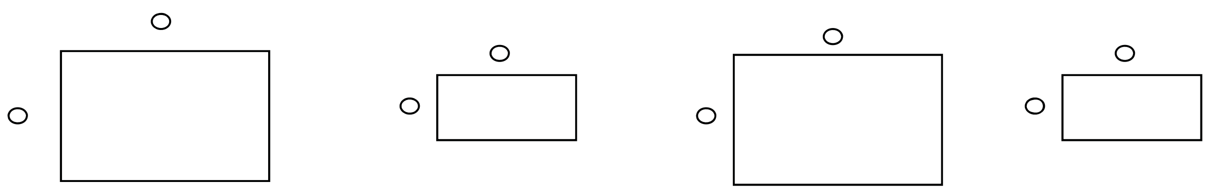
G11 & G18

Vancouver Calgary Friends Seinfeld



G12 & G19:

Vancouver Calgary Friends Seinfeld



Appendix D
Information sheet for participants

UNIVERSITY OF WATERLOO

INFORMATION SHEET FOR PARTICIPANTS

Title of Project: Investigating the effects of tabletop workspace design on group work.

Student Investigator: Sepinood Hajizadehgashti, Systems Design Engineering, 519-884-4567 x 37745

Faculty Supervisors: Dr. Stacey Scott, Systems Design Engineering, 519-888-4567 x 32236
Dr. Edward Lank, Computer Science, 519-888-4567 x 35786

Summary of the Project:

This project is part of a research program aimed at the design of multi-user, large screen computer interfaces, such as digital tabletop and wall displays. In order to develop effective interfaces for this technology, we need to understand what types of collaborative interactions these systems should support. Thus, this project focuses on understanding collaborative task and group interaction behaviour patterns on different types of tabletop workspaces. Through observation of participants performing collaborative tabletop activities the researchers hope to further understand common patterns of use related to tabletop space and task resources during tabletop collaboration. The information gathered in this study will be used to develop tabletop computer interfaces that support natural collaborative behaviour.

Procedure:

Your participation in this study will involve performing several social planning and layout activities at tabletop workspaces, over two sessions held on successive days. You will complete these activities with a partner.

A description of each activity follows.

Session 1 (to be completed today): You will receive an introduction to the experiment and then you will be asked to:

- Complete a collaborative tabletop activity with a partner. In the activity, you will either create a photo story using photos from a popular movie or television show, or produce a travel itinerary based on supplied tourist attraction pamphlets from a given Canadian city.
- Complete the same type of collaborative activity, using new materials, at a different tabletop workspace.
- Schedule your next session.

In Session 2 (to be completed on a subsequent day): You will return with the same partner. In this session you will be asked to:

- Complete the alternative collaborative tabletop activity listed above with your partner (e.g., travel planning if you completed the photo story task in Session 1, or vice versa).
- Complete the alternative collaborative activity again, using new materials, at a different tabletop workspace.
- Participate, with your partner, in a short interview with the experimenter related to the four collaborative activity trials you have performed.

Each session will take approximately 1 hour. During each session, a researcher will observe and take notes regarding your interactions with the activity resources and the tabletop, as well as your interactions with your partner in sessions. You will also be videotaped and any task materials produced during the session will remain with the researcher. You may withdraw your participation at any time without penalty.

Confidentiality and Data Security:

All information you provide is considered completely confidential. Your name will not appear in any publication resulting from this study; however, with your permission anonymous quotations may be used. In these cases participants will be referred to as Participant 1, Participant 2, … (or P1, P2, …) or collectively as a group (Group A, B, …). Data collected during this study will be retained indefinitely in locked cabinets or on password protected desktop computers in a secure location. Electronic data will not include personal identifying information such as names.

You will be explicitly asked for consent for the use of photo/video/audio data captured during the study for the purpose of reporting the study’s findings. If consent is granted, these data will be used only for the purposes associated with teaching, scientific presentations, publications, and/or sharing with other researchers and you will not be identified by name.

Compensation for Your Participation:

You will be compensated for your participation in this study, for a total of $20 if you complete both sessions. If you choose to withdraw your participation from the study prior to study completion, you will be compensated at the following rates:

Session	Hourly rate	Compensation for 1hour of participation
Session 1	$5/hour	$5
Session 2	$15/hour	$15
Expected Total Compensation		**$20**

Risks and Benefits:

There are no risks involved. Beyond the remuneration detailed above, there are no direct benefits to you. However, the results of this research may contribute to the knowledge base of Human Systems Engineering research and to lead to the development of digital tabletop workspaces.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes at this office at 519-888-4567 Ext. 36005.

Thank you for your assistance in this project.

Appendix E
Informed consent by subjects

UNIVERSITY OF WATERLOO

INFORMED CONSENT BY SUBJECTS TO PARTICIPATE IN A RESEARCH EXPERIMENT

Project: Investigating the effects of tabletop workspace design on group work.

I have read the information presented in the information letter about a study being conducted by Sepinood H.Gashti of the Department of Systems Design Engineering at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

Sometimes a certain image and/or segment of videotape clearly show a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific presentation or in a publication.

I am aware that I may allow video and/or digital images in which I appear to be used in teaching, scientific presentations, publications, and/or sharing with other researchers with the understanding that I will not be identified by name. I am aware that I may allow excerpts from the conversational data from this study to be included in teaching, scientific presentations and/or publications, with the understanding that any quotations will be anonymous.

I am aware that I may withdraw my consent for any of the above statements or withdraw my study participation at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director, Office of Research Ethics at 519-888-4567 ext. 36005.

	Please Circle One	Please Initial Your Choice
With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.	**YES NO**	____
I agree to be videotaped, photographed, and audio-taped	**YES NO**	____
I agree to let my conversation during the study be directly quoted, anonymously, in presentation of the research results	**YES NO**	____
I agree to let the Videotapes/Digital Images/Audiotapes be used for presentation of the research results	**YES NO**	____

Participant Name: ____ (Please print)

Participant Signature: ____

Witness Name: ____ (Please print)

Witness Signature: ____

Date: ____

Appendix F
Thank you letter for participants

Dear Participant,

I would like to thank you for your participation in this study. As a reminder, the purpose of this study is to understand task and group interaction behaviour with task resources and a shared workspace during tabletop collaboration.

The data collected during the study sessions will contribute to an improved understanding of design requirements for collaborative, large-screen display systems, such as digital tabletop and wall displays.

Please remember that any data pertaining to you as an individual participant will be kept confidential. Once all the data are collected and analyzed for this project, I plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. If you are interested in receiving more information regarding the results of this study, or if you have any questions or concerns, please contact me at either the phone number or email address listed at the bottom of the page. If you would like a summary of the results, please let me know now by providing me with your email address. When the study is completed, I will send it to you. The study is expected to be completed by December 31,.

As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes in the Office of Research Ethics at 519-888-4567, Ext., 36005.

Sincerely,

Sepinood H.Gashti

Master Candidate, Department of Systems Design Engineering

University of Waterloo

phone: 519-884-4567 Ext. 37745

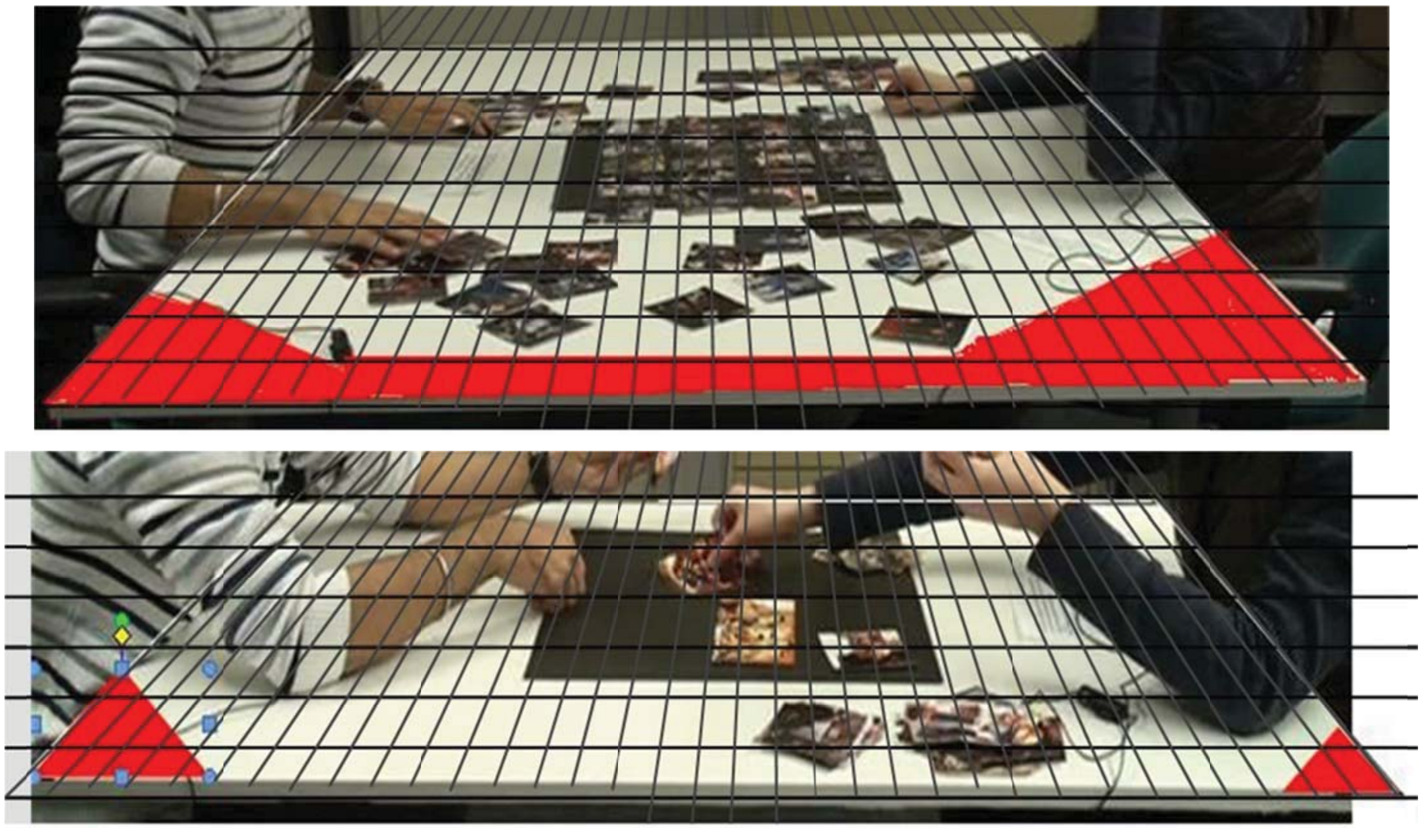
email: shajizad@uwaterloo.ca

Appendix G
Coding

This appendix is in the enclosed CD (for the sake of brevity). The content on the data disc is available from the Department of Systems Design Engineering, upon request.

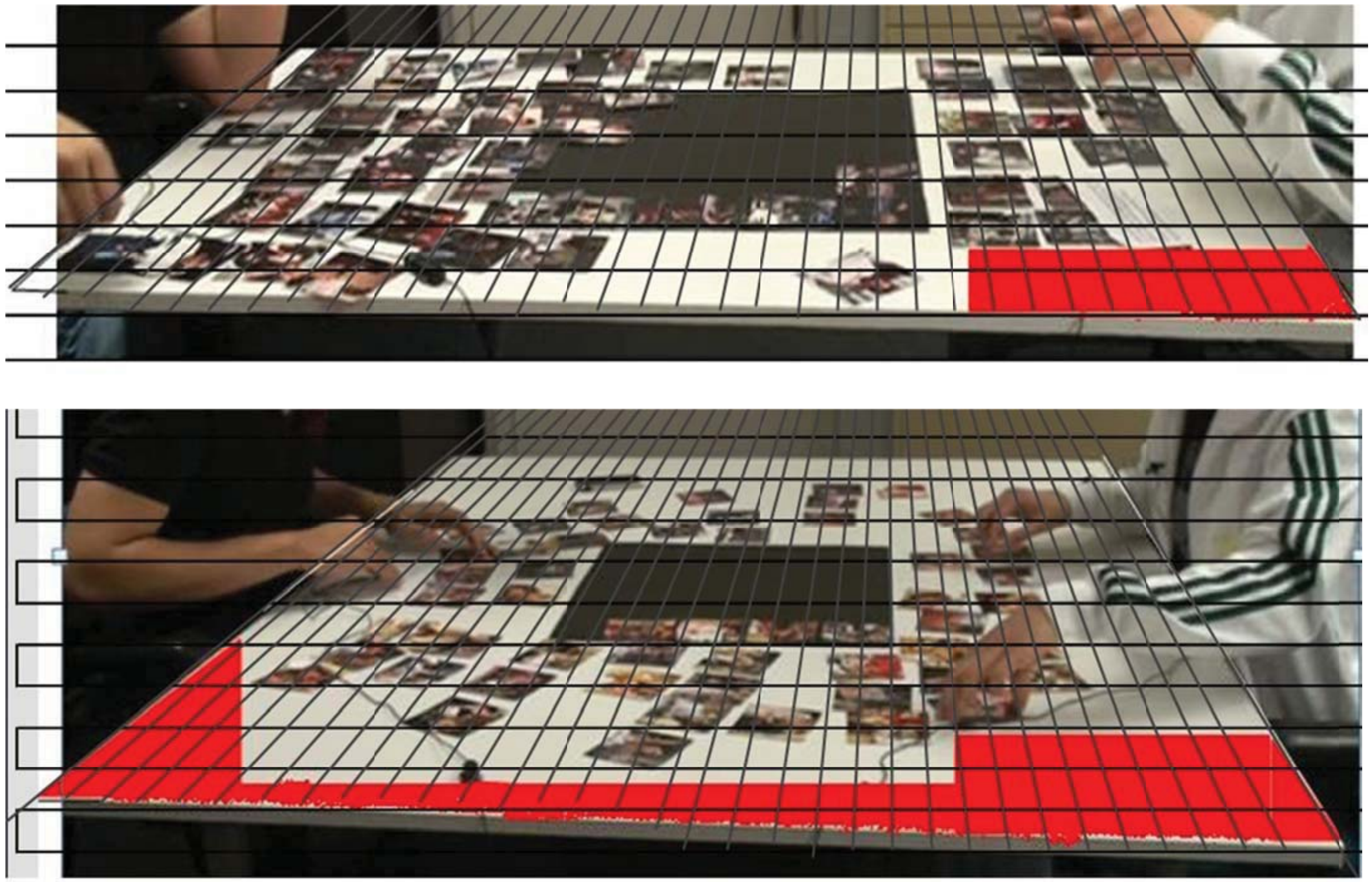
Appendix H

Spatial usage

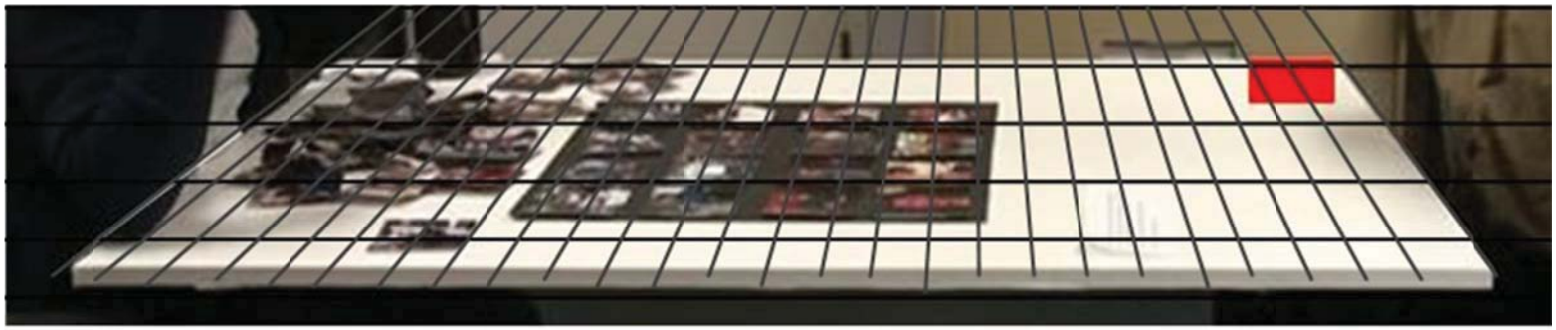


Across position – Storytelling – G2

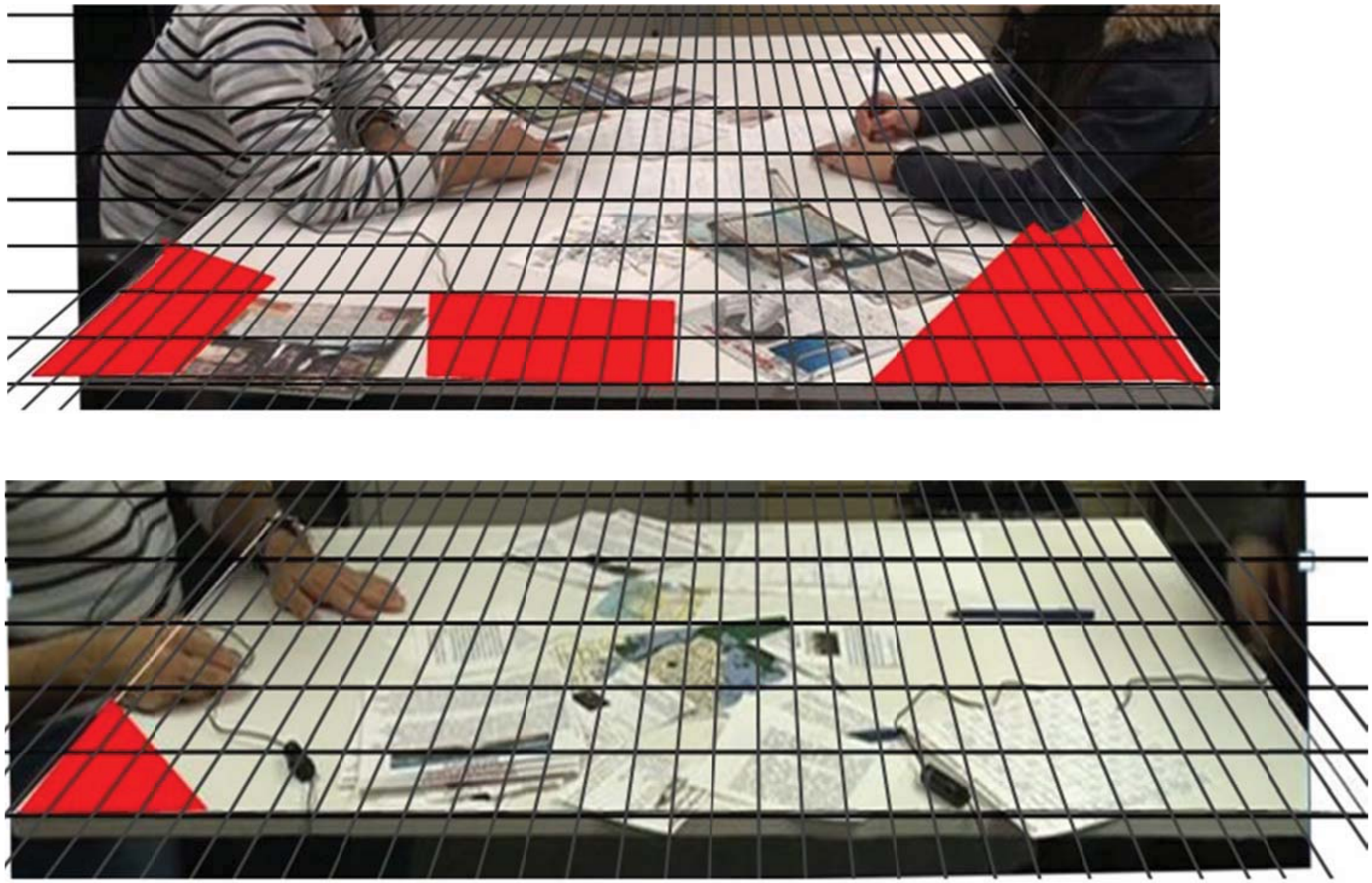
Across position – Storytelling – G6



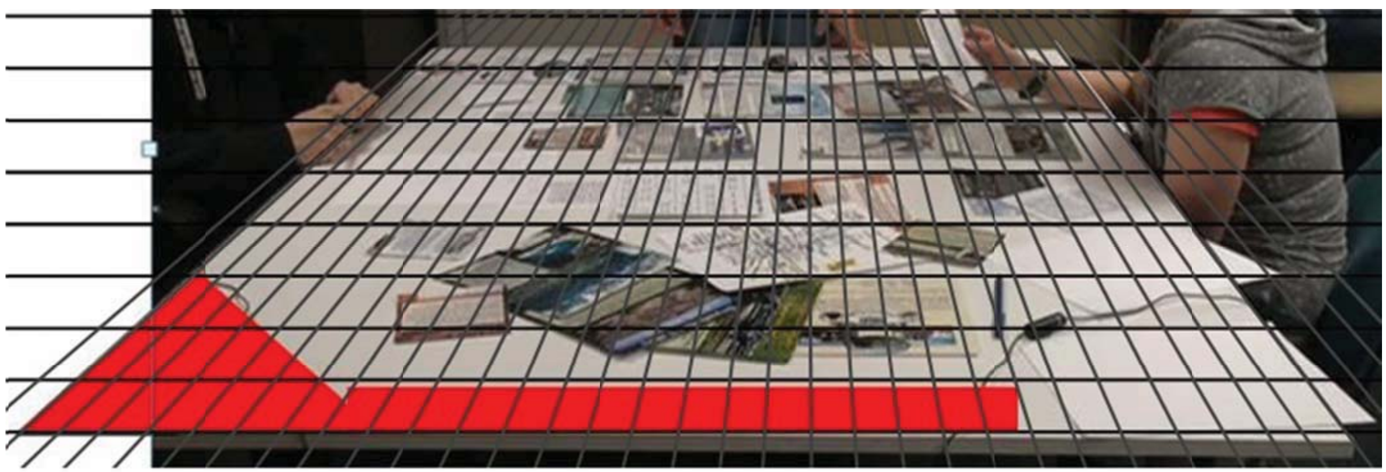
Across position – Storytelling – G7



Across position – Storytelling – G14



Across position – Travel planning – G2



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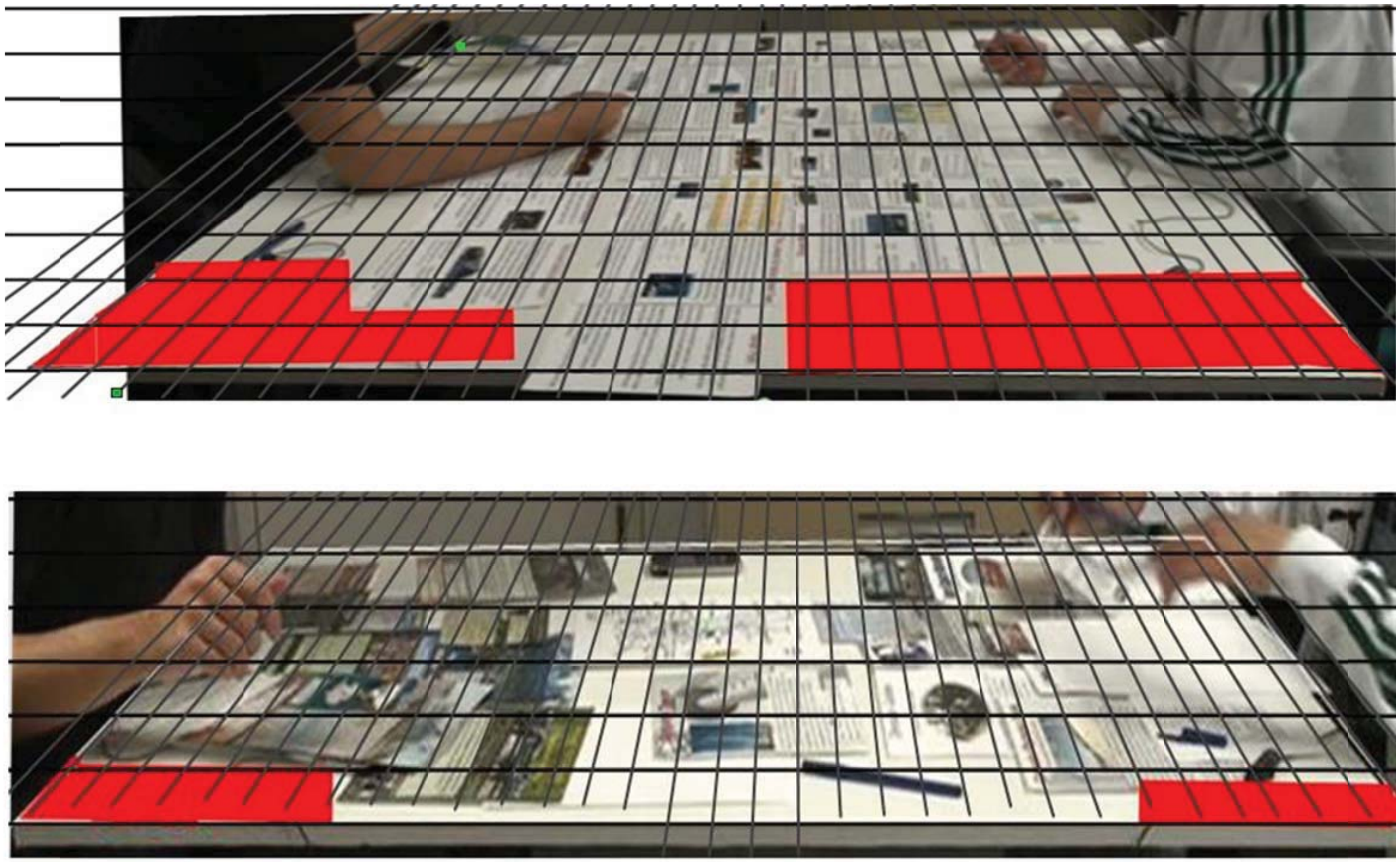

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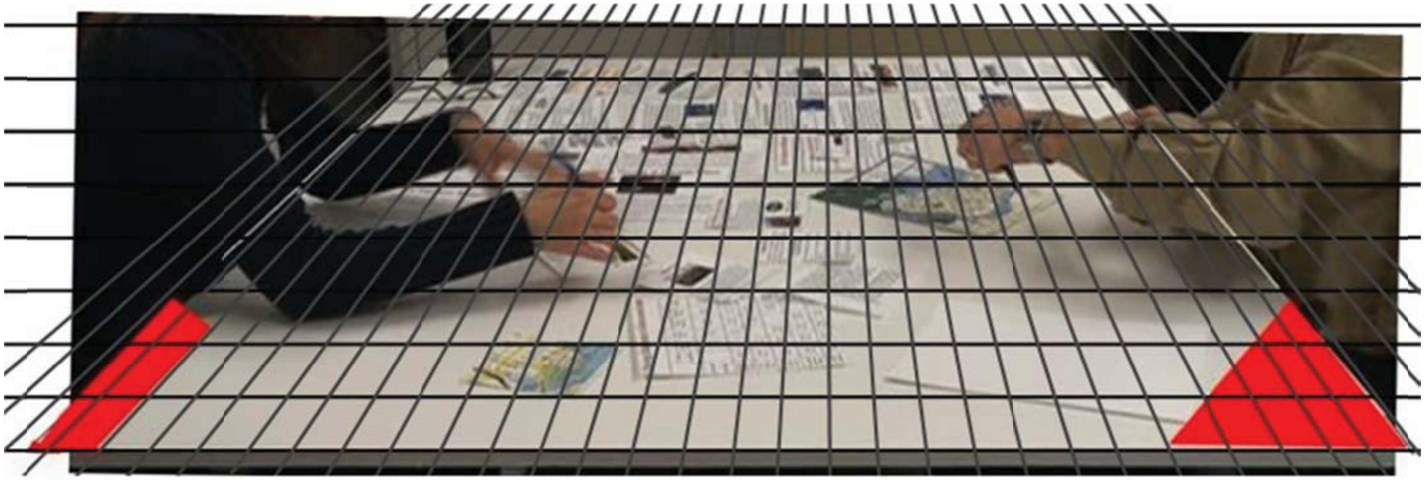
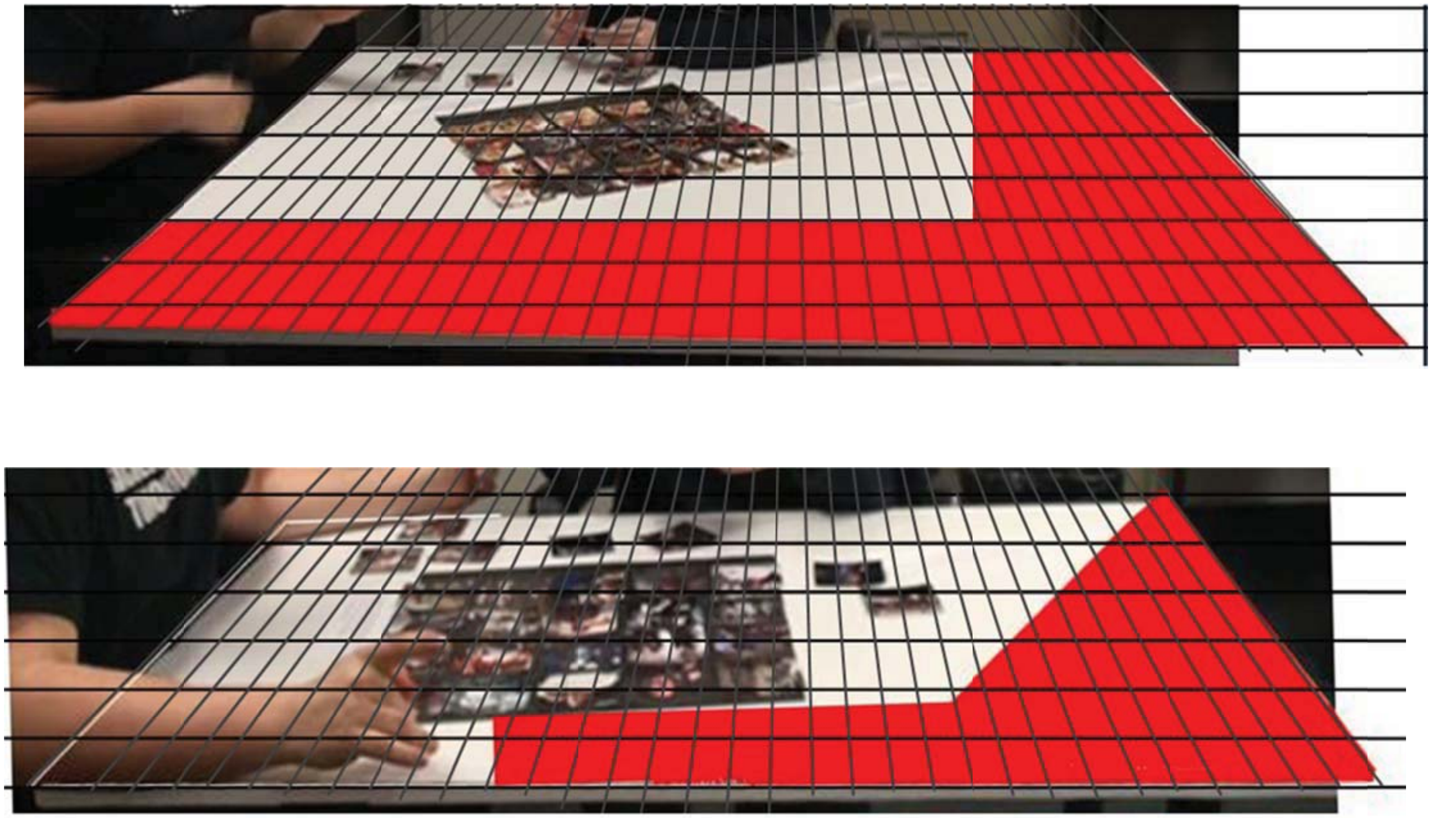
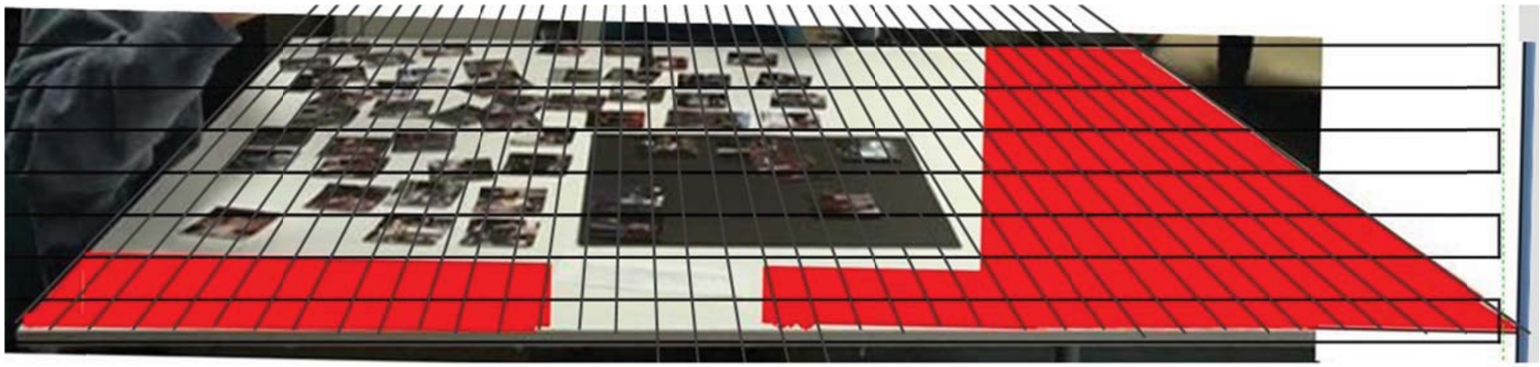


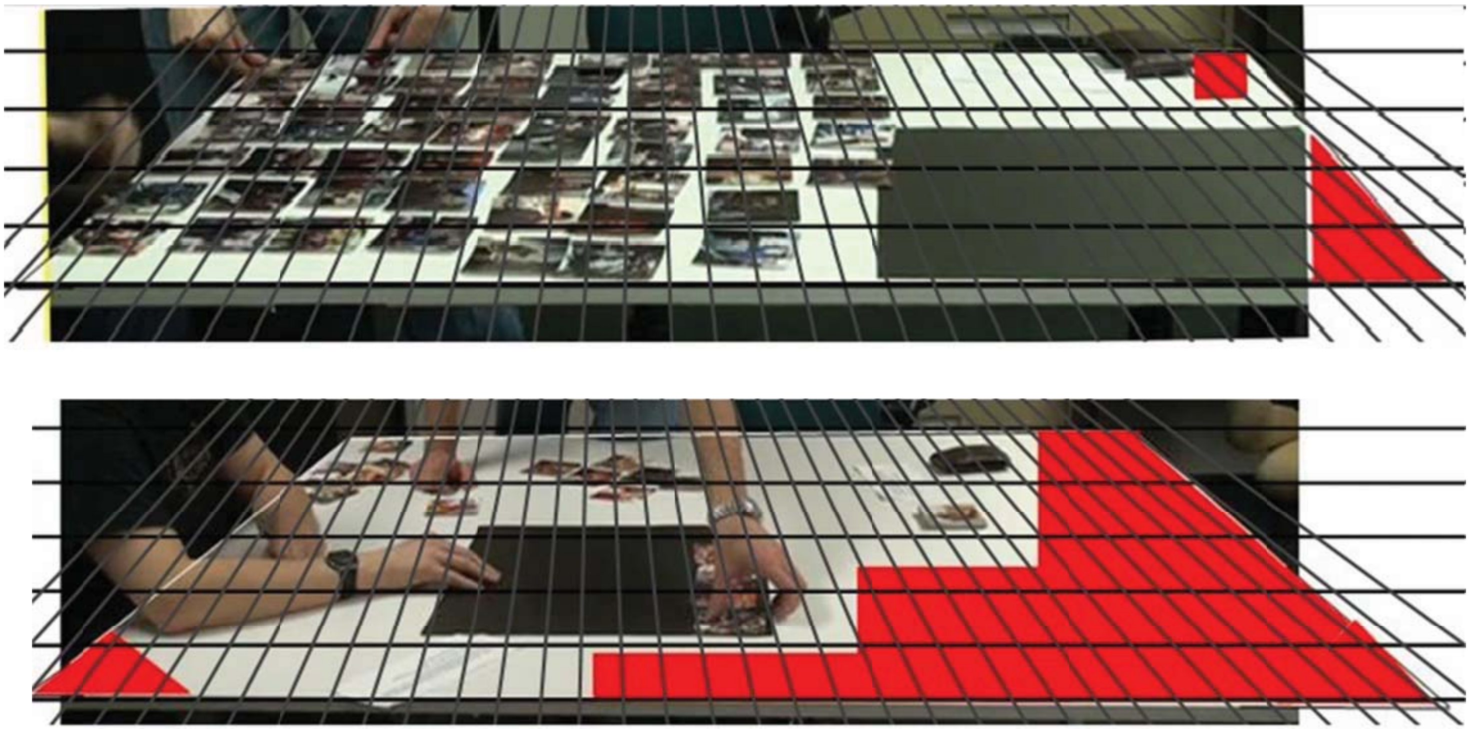
Across position – Travel planning – G14



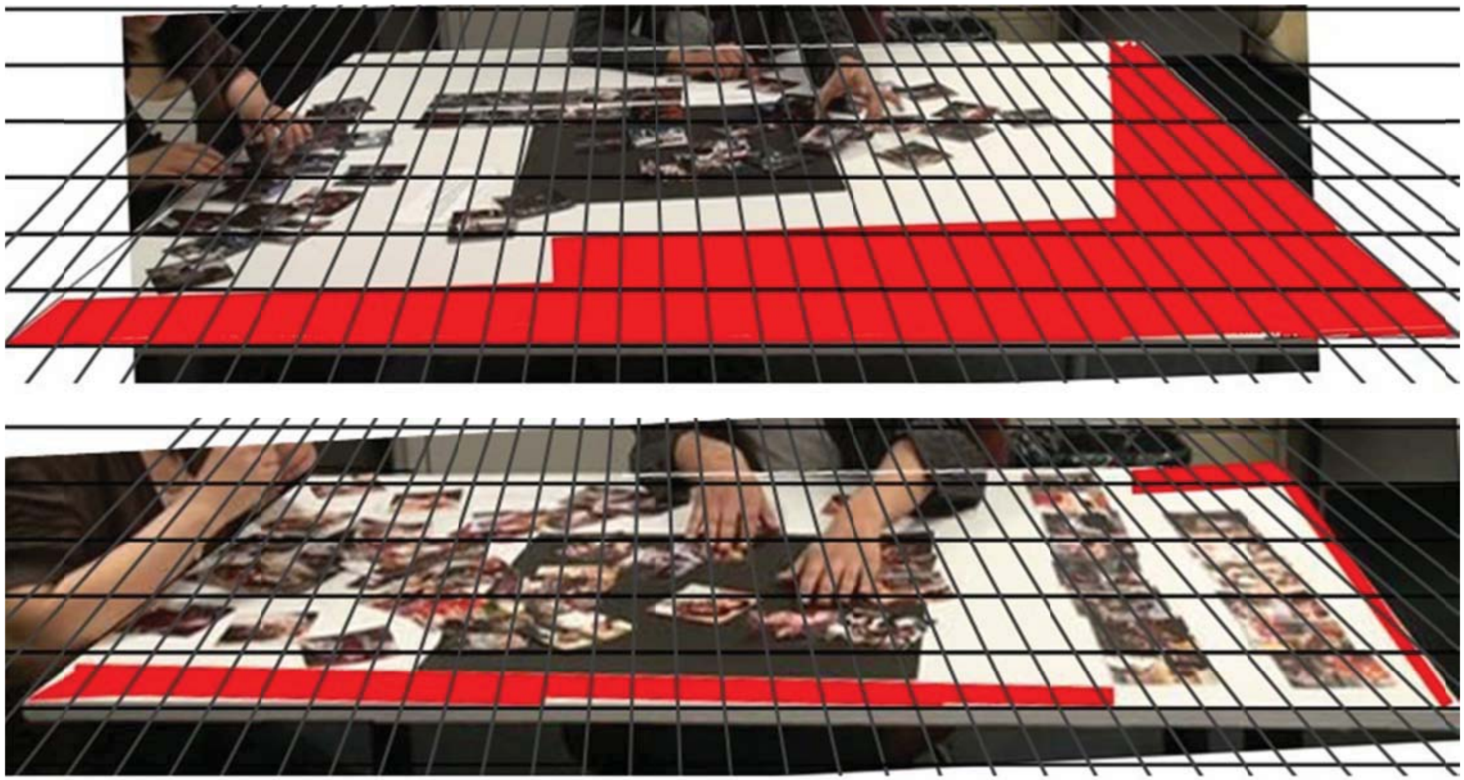
Corner position – Storytelling – G10



Corner position – Storytelling – G11

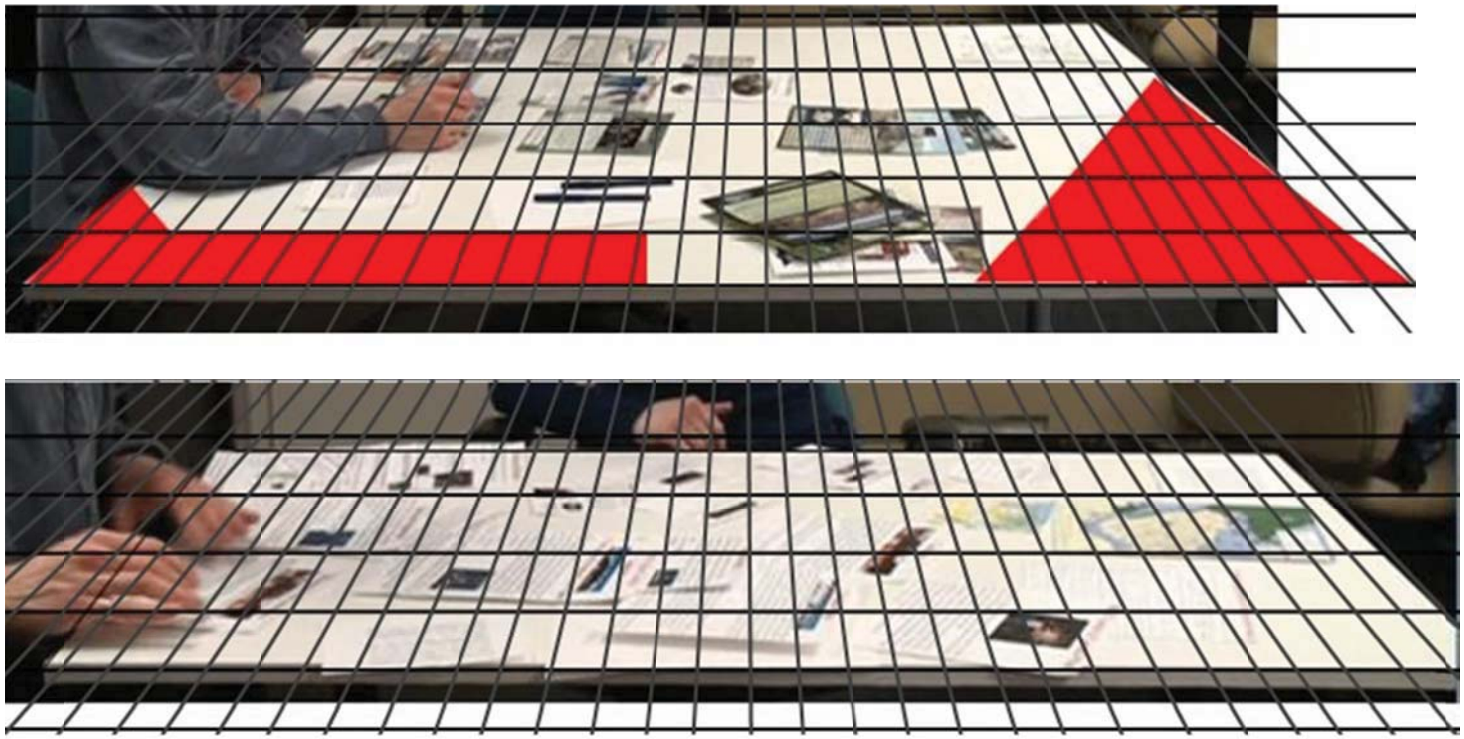


Corner position – Storytelling – G12

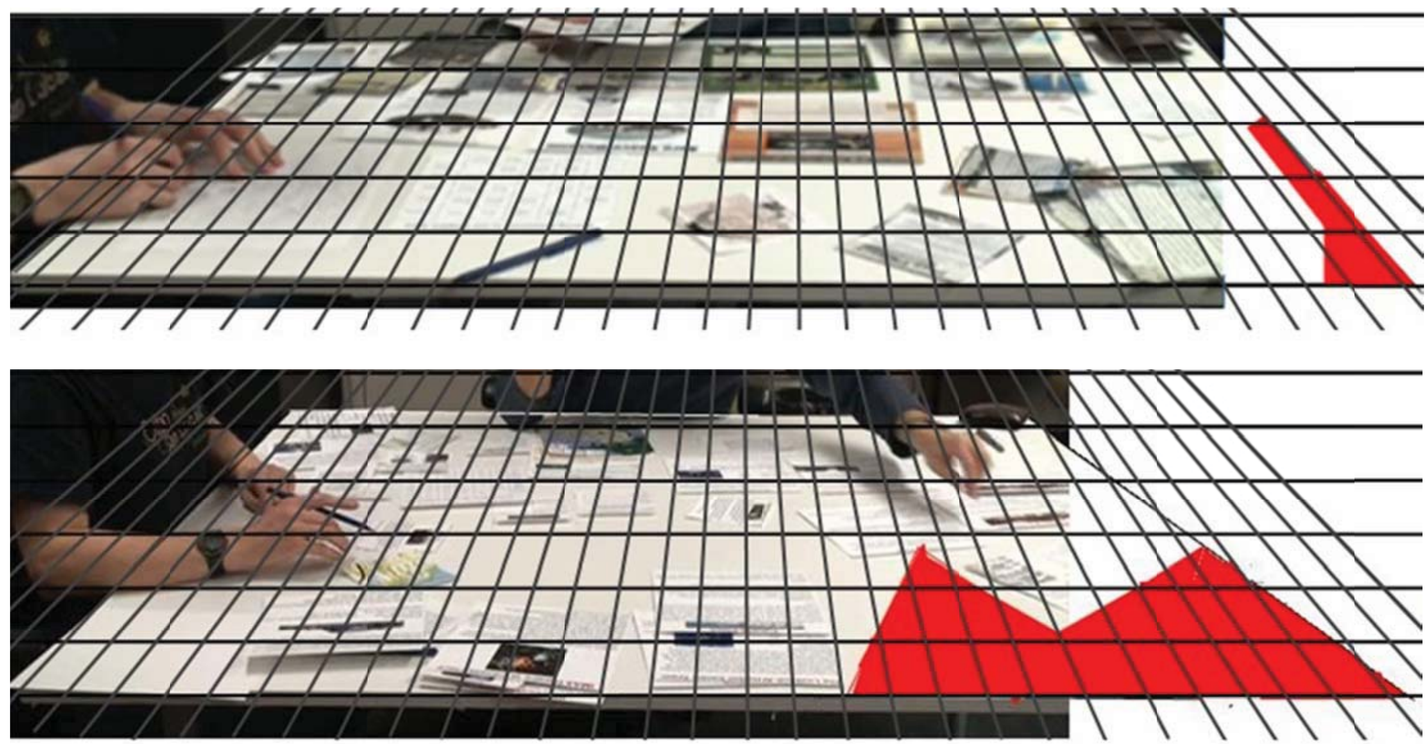


Corner position – Storytelling – G16

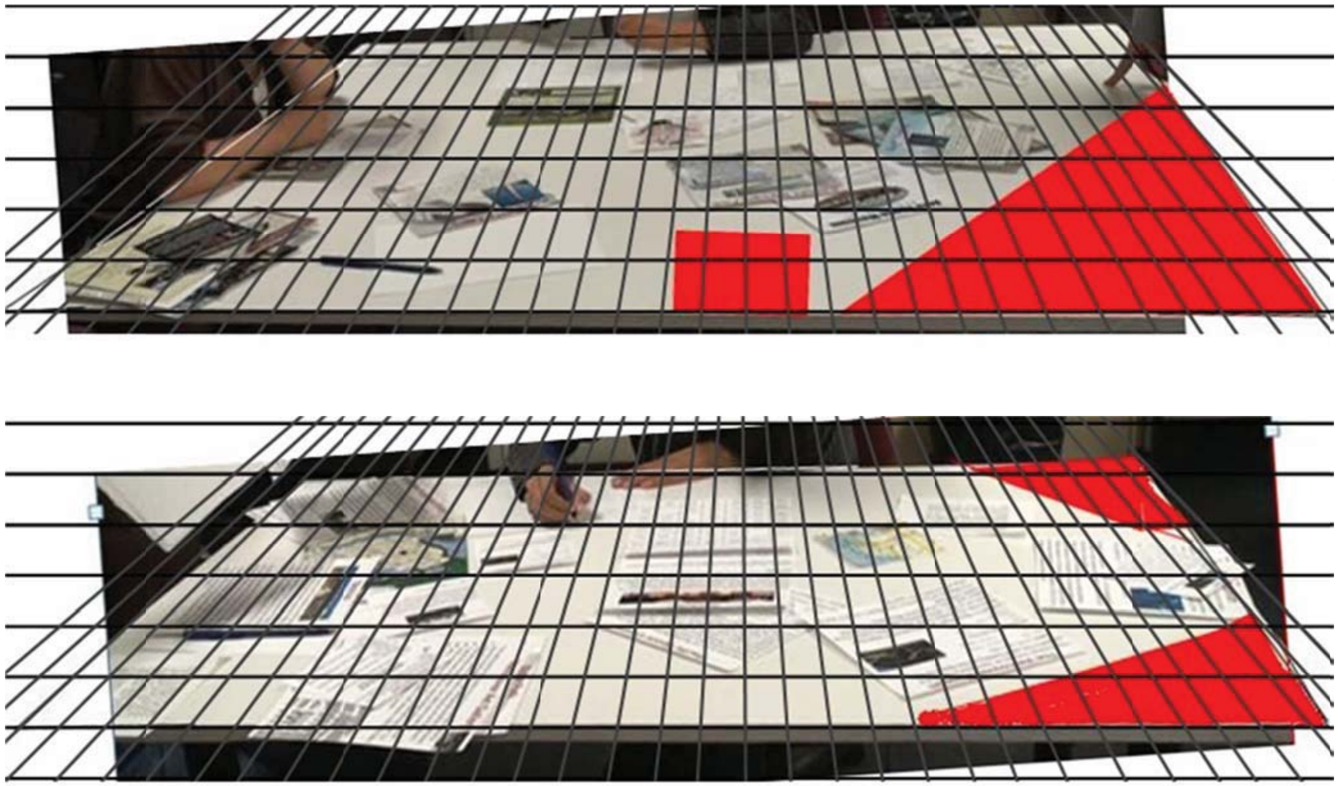
Corner position – travel planning   G10



Corner position – travel planning G11



Corner position – travel planning   G12



Corner position – travel planning G16

Appendix I

Reprinting Licenses

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Apr 23, 2012

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Number of figures/tables 1
Will you be translating? No
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Investigating the impact of table size on external cognition in collaborative problemsolving tabletop activities
Expected completion date May 2012
Estimated size (pages) 140
Billing Type Credit Card
Credit card info Master Card ending in 3092
Credit card expiration 10/2014
Total 8.00 USD

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