EXPLORING EYES-FREE USER MOTIVATION AND PREDICTING MENTAL WORKLOAD IN MOBILE HCI

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Summary

With an ongoing shift from desktop to mobile computing, it is timely to examine how interaction techniques can be optimized for mobile usage scenarios. This thesis presents an exploration of two important usability factors closely related to the design of mobile interfaces and interaction techniques – user motivation and mental workload. We first investigated user motivations for eyes-free mobile interaction. Eyes-free interaction, or interacting with mobile devices with little or no visual attention, is particularly attractive in mobile scenarios as the visual attention is often heavily taxed by mobility tasks. We presented a classification of motivations for eyes-free interaction under four categories (environmental, social, device features, and personal). Inspired by the observation on user motivations and design problems, we then explored the mental workload prediction methods for mobile HCI design especially in different mobile scenarios. Based on multiple resource theory [147] and W/INDEX [102], we derived a mental workload prediction method with two variants for dual-task conditions. Compared with the previous methods, our tailored method uses self-reported cognitive resource requirement scores instead of expert estimations for individual mobility and mobile HCI tasks, which significantly increases the practicality of the method to be used by designers and researchers. An experiment was conducted to validate our method with two variants and the results showed promising potential.

List of Publications

Exploring User Motivations for Eyes-free Interaction on Mobile Devices. *In ACM SIGCHI*, 2012. Bo Yi, Xiang Cao, Morten Fjeld, Shengdong Zhao, To Appear

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Chapter 1

Introduction

1.1 Problem and Motivation

With the development of mobile technologies and the recent success of the mobile industry, mobile Human-Computer Interaction (mobile HCI) has become one of the focused research areas in computing. However, as indicated by Dunlop and Brewster [38], there are many challenges for using mobile devices for computing tasks: mobility, a widespread population, limited input/output facilities, (incomplete and varying) context information and users multitasking at levels unfamiliar to most desktop users. To overcome these challenges, designers need to significantly improve the usability of mobile interaction techniques. By “usability” we mean the extent to which an interaction technique can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use [59].

When designing interactive systems, the first principle is to satisfy the needs and desires of the user [28]. Therefore, understanding the fundamental user motivations that drive the need and desire for specific interactive method is an essential step to achieving usable interaction techniques. The importance and urgency of understanding user motivations for mobile interaction techniques are especially reflected by the emergence of unconventional interaction techniques. A representative example is eyes-free interaction. Traditionally, interaction with and through mobile devices tends to rely primarily on users' visual attention. However, visual attention is a limited resource and is often heavily taxed by contextual factors in mobile environments. Researchers and designers have recently tried out alternative modalities such as acoustic and haptic to assist interaction with mobile devices and minimize the reliance on visual attention, also known as eyes-free interaction. However, there is a lack of systematic investigation into fundamental user motivations for eyes-free interaction on mobile devices.

In addition to understanding the user motivations, another important factor that deserves considerable attention from designers is the diverse usage scenarios with different design requirements in mobile computing. These scenarios range from walking in a street to driving a car. Each scenario can have a unique set of design requirements. Testing and assessing the effectiveness of a new design across different scenarios can be tedious and often infeasible. For example, while designing a mobile interface for in-vehicle use such as navigation, testing in the real driving condition is risky and resource-consuming (e.g., time and money). As a main factor in assessing human performance, mental workload, which indicates the relationship between resource supply and task demand [143], plays a crucial role. By quantifying the mental cost of performing tasks, designers can predict operator and system performance. This will be especially useful as performance measures cannot differentiate the different design choices, whereas mental workload can be used to assess the desirability of a system. Mental workload can be either measured in system evaluation or predicted without operators-in-the-loop. For designers, it will be a great help to estimate the mental workload of mobile HCI tasks in diverse scenarios in the early stage.

1.2 Overview of Our Work

This thesis explores two topics in mobile HCI: user motivations for eyes-free interaction on mobile devices and mental workload prediction in mobile HCI design.

While there is an increasing interest in creating eyes-free interaction technologies, a solid analysis of why users need or desire eyes-free interaction has yet to be presented. To gain a better understanding of such user motivations, we conducted an exploratory study with four focus groups, and suggested a classification of motivations for eyes-free interaction under four categories (environmental, social, device features, and personal). Exploring and analyzing these categories, we presented early insights pointing to design implications for future eyes-free interactions.

From the observation in the focus groups, we found that users always had the requirements for lowering perceived mental workload when choosing specific interaction technique, even in very diverse scenarios. However, as mentioned before, testing and assessing mental workload caused by a mobile interaction technique across different scenarios is costly. Although a number of theories and models such as VACP [2] and W/INDEX [102] have been proposed in the literature to help the estimation of mental workload, due to the requirement of expertise and the diversity of scenarios, applying them in practice to predict mental workload of mobile interaction techniques is difficult and has not been widely practiced.

In order to address this problem, we explored the mental workload prediction methods in mobile HCI especially in mobile scenarios. We focused on the situations where mobile HCI tasks (e.g., selecting the visual target on the screen) occurred in specific scenarios (e.g., walking in campus). Based on multiple resource theory [147, 148], we suggested a mental workload prediction method by integrating users self-reported data and modified W/INDEX model [122]. Then we conducted an empirical study through two phases – prediction and assessment – to evaluate our tailored method. By using the production of the requirements of shared resources to represent conflict level, we further simplified the prediction method for designers. Compared to the measured mental workload by using NASA TLX [51], our tailored prediction method and corresponding simplified version both showed high correlation.

1.3 Thesis Contributions

The main contributions of this work are twofold.

- First, from a user's perspective, we systematically examine motivations for eyes-free interaction on mobile devices, and further describe a categorization for them. By exploring the characteristics of user motivations for eyes-free interaction on mobile devices, we establish high level design implications for satisfying users' needs and goals.
- Second, we adapt the mental workload prediction methods based on multiple

resource theory and W/INDEX to propose a method to predict mental workload as users perform mobile HCI tasks under mobile scenarios. Although our method is preliminary in nature, this is the first attempt we are aware of in employing and studying mental workload prediction in mobile HCI. For researchers, our work can serve as a basis to inspire future improved mental workload prediction methods.

1.4 Thesis Organization

To better explain this work, this thesis is divided into five chapters.

Chapter 1 – **Introduction**: this chapter explains the problem/motivation, overview of our work and contributions of our work.

Chapter 2 – **Background and Related Work**: this chapter covers the discussion about 1) the related user motivation concepts, theories, and research methods; and 2) the related mental workload theories and measurement techniques as well as the importance in mobile HCI.

Chapter 3 – **Exploring User Motivations for Eyes-free Interaction on Mobile Devices**: this chapter presents the exploration of user motivations for eyes-free interaction on mobile devices.

Chapter 4 – **Exploring Mental Workload Prediction in Mobile HCI Design**: this chapter presents the exploration of mental workload prediction in mobile HCI design.

Chapter 5 – **Conclusion**: the work done in this thesis and future directions are summarized in this chapter.

Chapter 2

Background and Related Work

In this chapter we first review previous work related to user motivations, including concepts, theories, studies in HCI, and attempts in mobile eyes-free interaction. We then review the previous work related to mental workload including related definitions, theories, measurement techniques and challenges for mobile HCI designers.

2.1 User Motivation

In this section, we first review important concepts of motivation including the definitions and popular theories. Then we discuss previous studies about user motivations in HCI to get a deeper understanding of research methods. Lastly, we briefly review the related research about user motivations in eyes-free interaction on mobile devices.

2.1.1 Concepts of Motivation

In this section, we briefly review basic concepts of motivation to provide theoretical basis for our investigation on user motivations. We first discuss the definitions of motivation to form the proper definition which will guide our study. Then we briefly discuss three theories of motivation and related applications.

2.1.1.1 Definitions of Motivation

As previous work indicated, it is difficult to exactly define motivation [56, 66, 72, 82] exactly. The definitions in dictionaries are often some statements such as “Motivation is the cause of behavior”, which are fuzzy [56]. Theorists often described “motivation” by means of indicating the characteristics of motivations.

Early definitions – Kleinginna’s categorization for motivation definitions

A valuable work was done by Kleinginna et al. in 1981 [72]. They categorized more than 100 definitions/statements about “motivation” into 9 categories, on the basis of the phenomena or theoretical issues emphasized, as shown in Table 2.1.

Category	Characteristics
Phenomenological	Emphasizing conscious or experiential processes
Physiological	Emphasizing internal physical processes
Energizing	Emphasizing energy arousal
Vector	Emphasizing both energy arousal and direction
Directional/functional	Emphasizing choice, incentives, goal-directed behavior, or adaptive effects
Temporal-restrictive	Emphasizing immediate or temporary determinants of behavior
Process-restrictive	Distinguishing motivation from other processes
Broad/balanced	Emphasizing the complexity of motivation
All-inclusive	Incorporating all determinants of behavior

Table 2.1: The categorization of definitions of “motivation” (derived from [72])

At the end of their paper, they suggested one possible definition – “Motivation refers to those energizing/arousing mechanisms with relatively direct access to the final common motor pathways, which have the potential to facilitate and direct some motor circuits while inhibiting others”. However, as they indicated, it is still hard for others to accept this restrictive definition due to two reasons: first, the specific physiological mechanisms are difficult to identify completely. Second, the nonpsychologist commonly uses the term motivation in the all-inclusive sense.

Because we try to uncover the underlying needs and goals behind users' behavior, the definitions of motivation related to phenomenological, directional/functional and all-inclusive (because it may also refer to the previous two categories) ones are more meaningful for our research.

Recent definitions

Although the categorization provides a comprehensive view of hundreds of definitions of motivation, Kleinginna et al. [72] only investigated the work done before 1981. In order to understand more recent definitions, we did a quick search which mainly focused on the phenomenological, functional and all-inclusive definitions and found some representative ones shown as follows:

- Motivation is the psychological process that gives behavior purpose and direction [74]
- Motivation is a predisposition to behave in a purposive manner to achieve specific, unmet needs [19]
- Motivation is an internal drive to satisfy an unsatisfied need [53]
- Motivation is a general term applying to the entire class of drives, desires, needs, wishes & similar forces that induce an individual or a group of people at work [73]
- Motivation is a process that starts with a physiological deficiency or need that activates a behavior or a drive that is aimed at a goal incentive [118]

- A motive is a reason for doing something. Motivation can be described as goal-directed behavior [7]

The Definition Used in Our Work

As we can see, there are many related terms which emphasize different aspects of the concept of motivation. For example, “need” stresses the aspect of lack of want; “drive” emphasizes the impelling and energizing aspect; and “incentive” focuses on the goals of motivation. For our research, we try to define motivation in a more intuitive way by combining the phenomenological and functional properties. Although it could be all-inclusive in theorists’ view, in our mind, it is better to cover more related terms since we actually do not know how users will describe their motivations in an exploratory study. Therefore, *Motivation* in this thesis is defined as “*a general term applying to the entire class of goals, desires, needs, expectations and similar forces that induce specific behavior*”.

2.1.1.2 Theories of Motivation

There are numerous theories of motivation. It is not necessary to explain all of them in a limited space especially considering our research goal. Thus, we only focus on those which could inspire our research. Subsequently, these selected theories are briefly introduced, followed by the potential applications in HCI.

Maslow’s hierarchy of needs

Maslow's hierarchy of needs [91] shows that human needs can be grouped into different hierarchies, from low-level needs to high-level needs. It is often portrayed in the shape of a pyramid, as shown in Figure 2.1. The pyramid lists the most fundamental and basic five layers (physiological, safety, love/belonging, esteem, and self-actualization). This theory suggests the most basic level of needs must be met before the individual will strongly desire the secondary or higher level of needs.

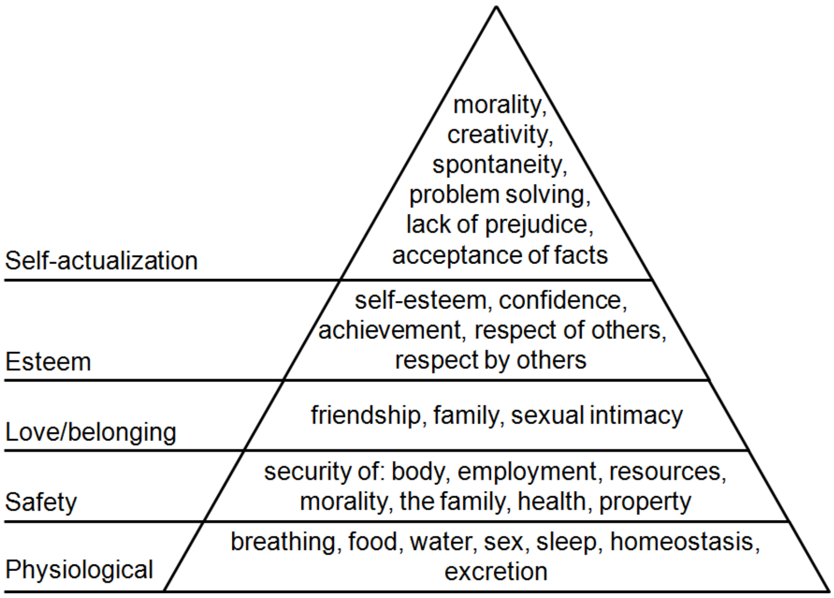

Figure 2.1: Maslow's hierarchy of needs

While investigating users' behavior for interacting with computing systems, Maslow's framework provides a useful view to treat users' application-specific or system-specific goals as instruments ultimately serving basic human needs [123]. Keeping this theory in mind has potential benefits for providing better user experience. For example, it suggests that multiple needs could be generated and met by the behavior of interacting with the specific systems. For example, a user who uploads a family photo to Facebook may simultaneously meet social and esteem needs, so in order to meet those two needs the designers could provide some mechanism such as "photo sharing" and "photo beautification". For our research, this theory can help to classify users' different needs in an abstract form.

Goal-setting Theory

A goal is what an individual is trying to accomplish; it is the object or aim of an action [86]. Sometimes, it can be replaced by similar concepts such as purpose, intent, and task, as Locke et al. listed in [86]. Goal-setting theory describes the process of how to set goals to motivate behavior and how to respond to goals. It identifies four mechanisms affecting behavior [84]:

- Direct attention: goals direct attention and effort toward goal-relevant activities and away from goal-irrelevant activities.
- Energizing: high goals lead to greater effort than low goals.
- Task persistence: it indicates the time spent on the behavior to accomplish a goal.
- Effective strategies: goals affect action indirectly by leading to the arousal, discovery, and/or use of task-relevant knowledge and strategies.

While invoking motivation through the above mechanisms, it is important to establish specific (what, where, how?), measurable (from and to), assignable (who?), realistic (feasible?) and time-targeted (when?) goals, as known as S.M.A.R.T goals [12].

As Locke and Latham argued [85], goal-setting can be used effectively on any domain where the control over the outcomes is required. Recently, researchers paid more attention to the application of goal-setting to investigate the relationship between technology and behavioral change. For example, by employing goal-setting in persuasive technologies, Consolvo et al. developed UbiFit system to encourage individuals to live healthy lifestyles

[27]. In contrast to applying this theory in practice, some theoretical work was also done based on goal-setting theory. For example, Oakley et al. draw the theoretical basis of a system intended to motivate sustainable behavior on goal-setting theory [108]. By introducing goal-setting in environmental HCI, Froehlich et al. investigated the design of eco-feedback technology [42]. For our research, within the framework of goal-setting, it is helpful for us to identify users' goals and further find the underlying elements that affect the transition from goals to behavior.

Expectancy Theory of Motivation

In contrast to Maslow's hierarchy and Goal-setting, expectancy theory stresses and focuses on outcomes rather than needs and goals. The expectancy theory of motivation provides an explanation as to why an individual chooses to act out a specific behavior as opposed to another [140]. According to this theory, motivated behavior is a product of three key variables:

- Expectancy: it can be described as the belief that higher or increased effort will yield better performance. E.g., "If I work harder, I'll make something better".
- Instrumentality: it can be described as the belief that successful performance will be followed by rewards. E.g., "If I make it better, I'll get more rewards".
- Valence: it means "value" of the outcome and refers to beliefs about outcome desirability. E.g., "Do I find the outcomes desirable?"

Thus, the motivational force (MF) can be summarized by the following formula (VIE):

$$MF = Expectancy \times Instrumentality \times Valence$$

In practice, all variables are measured based on perceived report and the value of each variable is in a limited range. Table 2.2 shows the ranges [115].

Variables	**Range**	**Range definition**
Expectancy	0 to 1	0 = belief the individual could not perform successfully 1 = firm belief the individual could perform successfully
Instrumentality	0 to 1	0 = no relationship between performance and outcome 1 = outcome dependent on performance
Valence	-1 to +1	-1 = avoidance of outcome 0 = indifference +1= expected outcome would be satisfactory

Table 2.2: The range of variables in VIE formula

Although expectancy theory was well known in work motivation literature, within the increasing usage of information technologies in workplaces researchers tried to apply it to HCI. For example, DeSanctis examined the appropriateness of expectancy theory as an explanation of voluntary use of a decision support system [35] and she found that users' positive attitudes towards information systems increased the actual use of the system. Similarly, Burton et al. [19] evaluated the appropriateness of expectancy theory in examining user acceptance of an expert system and their results showed that users will continuously evaluate the outcomes of a newly implemented system use and subjectively assess the likelihood that their actions will lead to desired outcomes. This theory can help us understand the importance of users' expectations for using specific technology.

2.1.2 User Motivations in Human-Computer Interaction

In order to get an overview about how user motivations were studied in HCI, we conducted a paper survey based on the criterion that the paper should focus on exploring what motivates users to use specific computer system/technology. Based on the purposes of the computer technology mentioned in previous work, we categorized those papers into three categories: education, work and life/leisure.

- Education: the work in this category focuses on the motivations in e-learning (e.g., [78]) or the technology itself has significant educational meaning (e.g., Wikipedia [103]).
- Work: the work in this category focuses on the motivations in facilitating users to choose and use computer technology to help work performance. E.g., using computers in the workplace [33], using expert system [19], and participating in open source projects [48].
- Life/Leisure: this category is the broadest one which includes all the work which is not related to obvious educational and work purpose. The work in this category focuses on what motivates users to choose and use computer system/technology to enjoy life. E.g., photo tagging [3], SNS [63], and entertainment [142].

For each category, according to the typical situation where the user is described by previous work, those works can be further categorized into three sub categories: individual, social and balanced.

- Individual (Abbreviated as "I"): choosing and using the specific computer system/technology is more related to an individual behavior. E.g., consuming mobile video [107] and using search engine [119].
- Social (Abbreviated as "S"): choosing and using the specific computer

system/technology is more significantly affected by other users. E.g., using online communities like Facebook [37] and participating in open source projects [52].

- Balanced (Abbreviated as “B”): choosing and using the specific computer system/technology is not clearly indicated. E.g., the common usage of mobile phones [80].

Besides the purposes and social properties, we were interested in the methodologies used in previous work because they can guide the design of our study. We first differentiated two types of methods: theory-based analysis and exploratory investigation. The former emphasizes the use of specific theories in investigating user motivations. The latter is independent of specific theories and more opening. We further looked at the methods of data collection and data analysis in previous work. Subsequently, we discuss how previous work reflects those different issues.

2.1.2.1 Theory-based Analysis vs. Exploratory Investigation

According to whether the specific theory was used, we categorized previous work into two categories: theory-based analysis and exploratory investigation, as shown in Table 2.3.

		Purpose								
		Education			Work			Life/Leisure		
		I	S	B	I	S	B	I	S	B
Methods	Theory-based analysis	[78]	[103]		[19, 33, 58]	[48, 52, 75]		[119, 127, 134]	[24, 76, 77, 141, 142]	[80, 104]
	Exploratory investigation					[6, 37]		[3, 18, 25, 64, 70, 106, 126, 133]	[3, 63, 125]	[10 6]

Table 2.3: The classification for previous research about user motivations: theory-based analysis vs. exploratory investigation

Theory-based analysis

Previous work focusing on theory-based analysis tried to investigate user motivations in theoretical frameworks. In this section, we introduce the two most used theories: Technology Acceptance Model (TAM) and Uses & Gratifications Theory. Then we briefly introduce other theories used in previous work to help the investigation of user motivations.

Technology Acceptance Model (TAM)

Technology Acceptance Model was developed by Davis et al. [33, 34] and has been widely used to evaluate users' behavior and motivations in computer and software adoption and usage [79].

As shown in Figure 2.2, TAM suggests that Information Technology usage is determined by behavioral intension. Behavioral intention is affected by attitude toward usage and indirectly by perceived usefulness (PU). Attitude towards usage is directly affected by perceived usefulness (PU) and perceived ease of use (PEOU). Perceived ease of use (PEOU) has a direct impact on perceived usefulness (PU). Perceived usefulness is defined as “the degree to which a person believes that using a particular system would enhance his or her job performance” [32]. Perceived ease of use (PEOU) is defined as “the degree to which a person believes that using a particular system would be free from effort” [32]. Later, Davis et al. [33] added a new factor – perceived enjoyment (PE) to adopt TAM from both extrinsic and intrinsic motivational perspectives. Perceived enjoyment (PE) is defined as “the extent to which the activity of using the computer is perceived to be enjoyable in its own right, apart from any performance consequences that may be anticipated” [33] and is affected by perceived ease of use (PEOU).

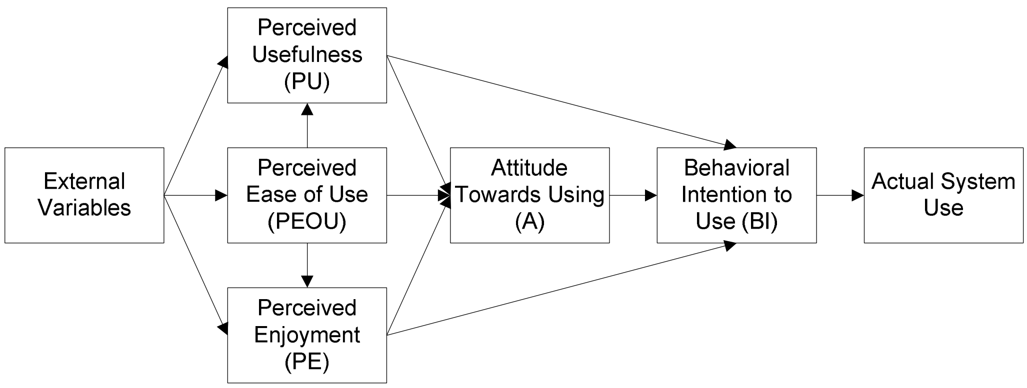

Figure 2.2: TAM with perceived enjoyment

To use this model to investigate user motivations, typically a questionnaire based on Likert scale is designed first to get users’ perceived usefulness, ease of use and enjoyment (see [32] to get more details about how to design this questionnaire). Data is usually analyzed by using factor analysis and regression analysis. The purpose of analysis is to find the relationship among different motivational factors and the effect on the actual system use. For example, by investigating intrinsic and extrinsic motivations, Teo et al. found that Internet users were motivated to use Internet mainly because they perceived the Internet more useful for their job tasks and they perceived enjoyment and ease to use [134]. Lee et al. did a similar work to investigate students' extrinsic and intrinsic motivations for using an Internet-based learning medium to show the success of integrating a motivational perspective into the TAM [78].

As argued in [25], currently, the TAM model has some limitations such as the unreliable self-reported use data, and simplistic relationship between the variables. For our research, the main concern about adopting TAM is that it is a good way to analyze the relationship between different motivational factors but it relies on the design of the questionnaire and lacks exploration of underlying user motivations but cannot help researchers find the closet user motivations from scratch.

Uses and Gratifications Theory

Uses and Gratifications theory is a media use theory explaining why people use a particular media from mass communications [14]. There are two kinds of gratifications: the ones sought by the users and the ones actually obtained from the use of the media [112]. It suggests that people play an active role in choosing and using the media. That is, in the communication process, users are goal-oriented. It emphasizes the role of motivations in media use. The common needs for media use could be categorized into five categories: cognitive needs, affective needs, personal integrative needs, social integrative needs and tension release needs [69]. With the increasing use of computer technologies, the emergence of computer-mediated communication has revived the significance of uses and gratifications [120].

The applications of this theory in HCI focused on two kinds of media: the Internet and the mobile phone. Researchers treating the Internet as mass medium exploited this theory to find the motivations for specific Internet usage such as online community. For example, Rafaeli et al. [114] categorized contributors' motivations for Wikipedia into three categories: getting information, sharing information and entertainment. Lampe et al. [77] examined the motivations of users for a online community – Everything2.com and found that feelings of belonging to a site were important motivators. Researchers also used this theory to understand motivations for mobile phone usage. For example, Leung et al. [80] investigated users' needs while using mobile phones. Wei [142] drew on this theory to examine the motivations for using the mobile phone for mass communications and entertainment. Stafford et al. [127] adopted it for M-commerce and found that mobile device uses and gratifications were centered on the speed and connectivity.

For critics, users may not be really active and controlled [87] and the validity of self-reported data is also doubtful especially within the complexity of human motivation [124]. Both of these limitations could lead to the loss of "hidden motivations" in the computer-based media use, which should be avoided in our research on investigating user motivations.

Other theories

Besides the above two theories, researchers also tried to draw on other theories to investigate user motivations in HCI. For example, based on the basic theories about intrinsic and extrinsic motivations, Lakhani et al. [75] investigated the motivations of people to contributing to Free/Open Source software. Burton et al. [19] conducted a study to examine the use of expectancy theory in explaining the motivation to use an expert system.

Exploratory investigation

In contrast to providing deep theory-based analysis, some researchers focused more on the opening outcome of the explorations for user motivations without relying on any specific theoretical framework. This kind of research focused on the analysis of situations where the user is and tried to define the potential problems for further research (it is known as “exploratory research” in social science [128]).

Exploratory investigation is adopted by researchers often due to the complexity of user motivations and the requirement of clarifying and defining the nature of the problems especially while the studied problem (e.g., mobile 3D TV [64]) is new and lacks deep understanding (e.g., using camera phone [70]). In previous work, it often relied on qualitative research methods such as participant observation, interviews and focus groups. The outcome of those work focused on enhancing understanding with design or research guidelines for uncovered problems. For example, Hara [106] explored user motivations for participating geocaching by conducting both diary study and in-depth interview and indicated the implications for future systems. Ames et al. [3] deeply investigated user motivations for annotation in mobile and online photos and suggested design implications for the design of digital photo organization and sharing applications as well as the applications for incorporating user-based annotation.

2.1.2.2 Data Collection

In this section, we further categorized previous work based on the specific methods for data collection to get more inspirations. Typically, in a user study, user data can be collected by using survey, interview, diary and experiment. Subsequently, we take a brief look at those data collection methods and related previous work. Table 2.4 shows a complete classification.

		Purpose								
		Education			Work			Life/Leisure		
		I	S	B	I	S	B	I	S	B
Data Collection	Survey	[78]	[103]		[33, 58]	[48, 52, 75]		[18, 64, 127, 134]	[76, 77, 141, 142]	[80, 104]
	Interview					[6, 37]		[3, 64, 70, 107]		[106]
	Diary							[25, 107, 126, 133]		[106]
	Experiment				[19, 33]	[37]		[119]	[24]	

Table 2.4: The classification for data collection methods in previous work

Survey

Survey usually indicates the compilations of questions that are implemented either via a computer or paper-and-pencil-based environment that either have quantitative or qualitative scales, or are open-ended, and that target at extracting a variety of information from a representative sample of the target population [30].

The main advantage of survey is that it can collect a large number of data with relatively little effort from representative samples. Survey is widely used in understanding user motivations, as shown in Table 2.3. We noticed that most of those papers were theory-based analysis. For example, based on TAM, Teo et al. [134] designed an online survey to investigate users' intrinsic and extrinsic motivations in Internet usage. Based on Uses and Gratifications theory, Lampe et al. [76] developed an online survey and investigated user motivations for participating in online communities. A possible explanation is that those theories already indicated the measurements which can be easily collected by using survey.

However, the disadvantage of survey is also very obvious. It relies highly on the subjective feedback of respondents and only can provide snapshots of studied phenomena. It lacks the mechanism for researchers to find the underlying factors behind the user's choice. Therefore in exploratory investigation for user motivations, survey is used rarely.

Interview and focus groups

Typically, an interview is a conversation between the interviewer and the interviewee where the interviewee is asked to gather useful information for the interviewer.

As data collection tools, there are three different categories of interviews: structured interviews, semi-structured interviews and unstructured interviews. In structured interviews, interviewees are often required to answer “yes” or “no”. In contrast, in unstructured interviews, interviewees can dictate the content and progress of the interview. Semi-structured interview is between structured and unstructured interview. It is flexible and allows new questions to be brought up during the interview as a result of what the interviewee says. While interviewing users for their motivations, researchers often took into account the semi-structured interview (e.g., [3]) because without any inspiration it is hard for users to report related behavior and meanwhile users may propose more useful information beyond the questions. However, interviews are often time-consuming especially when there are many interviewees. Besides, the quality of the gathered data is dependent on both the skill of the interviewer and the openness of the interviewee.

Focus group is “a technique involving the use of in-depth group interviews in which participants are selected because they are a purposive, although not necessarily representative, sampling of a specific population, this group being ‘focused’ on a given topic” [135] and it is particularly suitable for early exploration in identifying new problems and assessing users’ needs [98]. For example, Jumisko et al. [64] held focus groups to investigate users’ requirements for mobile 3D TV and video. Focus groups are less time-consuming than interviews and can facilitate the exploration of common experiences of participants. However, the quality of the data is highly influenced by group dynamics and the skill of moderators.

Diary study

In diary study, participants are asked to record their activities on a prepared log form. The activities could be recorded daily, weekly or when the event occurs. It is a good way for researchers to investigate user motivations because it can achieve a relatively high standard of objectivity [117] and increase the credibility of the gathered data. For example, in order to understand the intent behind mobile information needs, Church et al. [25] asked participants to keep a diary of all their information needs while they were at home, at work or mobile. The main advantages of diary study are to minimize the problems caused by inaccurate memories and to capture the phenomenon which is hard to observe. However, participants accept most of the responsibility for data collecting and it is hard to confirm the accuracy of the data.

Experiment

The experiment discussed here is a relatively broader concept. It refers to the process where data is collected after participants finish a series of designed tasks. Experiments are often used for understanding motivations in new or very specific computing systems where participants may lack related experience. In that case, researchers often designed several experiments to help participants gain the experience and record their usage behavior. For example, in the study carried out by Burton et al. [19], participants were asked to experience a judgment modeling decision-making exercise for the expert system implementation context before assessing their motivations. Similarly, in order to understand users' extrinsic motivation in a specific collaborative information finding system, Shapira et al. [125]

designed a long-term experiment to increase participants' experience. Experiments can increase the quality of data. However, the experiment is often time-consuming and hard to design.

2.1.2.3 Data Analysis

Based on the method for data analysis, previous work can be categorized into two categories: quantitative analysis and qualitative analysis, as shown in Table 2.5.

		Purpose								
		Education			Work			Life/Leisure		
		I	S	B	I	S	B	I	S	B
Data Analysis	Quantitative	[78]	[103]		[19, 33, 58]	[6, 37, 48, 52, 75]		[18, 25, 64, 119, 127, 134]	[24, 76, 77, 141, 142]	[80, 104]
	Qualitative					[6, 37]		[25, 64, 70, 107, 126, 133]		[106]

Table 2.5: The classification for data analysis methods in previous work

Quantitative analysis is the process of presenting and interpreting numerical data. Statistical models are used to get the explanation of gathered data. Internal validity is concerned with the support that the causal variable caused the effect in the effect variable. External validity is concerned with the support for the generalization of the results beyond the study sample. Typically, it is used for large, random and representative samples. While investigating user motivations, researchers often used quantitative analysis to describe the relationship between different motives and the relationship between motives and behaviors. The quantitative analysis methods which were used often are descriptive statistics (e.g., [104]), factor analysis (e.g., [33]), regression analysis (e.g., [80]) and so on.

Qualitative analysis is the process of interpreting data collected by using qualitative methods. The aim of qualitative analysis is to generate detailed and interpretive findings rather than proving statistical causality. The samples are usually collected from small, purposeful and nonrandom population. The most often used method for qualitative analysis in previous work is grounded theory [130], which emphasizes generation of theory from data in the process of conducting research. For example, Taylor et al. [133] used this theory to generate a new preliminary framework for understanding users' motivations and behaviors based on qualitative data.

2.1.3 User Motivations in Eyes-free Interaction

In eyes-free interaction, the tasks are accomplished without using visual attention. While many innovative technologies with eyes-free interaction capabilities have been introduced [8, 16, 65, 68, 81, 138, 157], there is a lack of systematic investigation into the fundamental user motivations that drive the need and desire for eyes-free interaction on mobile devices. Instead, most researchers focused on technical details. Only a few researchers mentioned the importance of users' needs or goals for their eyes-free interactive technologies.

Brewster et al. [16] mentioned that while users were interacting with mobile devices while walking, running or driving, it must remain with the main task (e.g., walking) for safety and current mobile visual displays were hard to use in bright daylight. Ashbrook et al. [8] emphasized that using a magnetically-tracked finger ring as mobile input can satisfy users' social needs and enhance social acceptance. Li et al. [81] developed an auditory interface to satisfy users' needs for accessing stored data as part of a phone conversation. Zhao et al. [157] described five possible factors which may drive users to utilize eyes-free interaction: 1) competition for visual attention; 2) absence of a visual display; 3) user disability; 4) inconvenience; 5) reduction of battery life.

2.1.4 Summary

In this work, Motivation is defined as "a general term applying to the entire class of goals, desires, needs, expectations and similar forces that induce specific behavior". User motivations have been studied extensively in HCI and a lot of methods can be used. However, there is a lack of systematic investigation into the fundamental user motivations for eyes-free interaction on mobile devices. We believe that filling this gap will be essential for future researchers and designers. Consequently, in chapter 3 we aim at exploring user motivations for eyes-free interaction on mobile devices.

2.2 Mental Workload

In this section, we first review the work related to attempts for understanding the definition of mental workload. Then multiple resource theory and related applications are reviewed to help to establish the knowledge base for task and cognitive analysis. Then we review mental workload measurement techniques for prediction and assessment. Lastly, we briefly review the challenges in mobile HCI and how mental workload has been studied in mobile HCI field.

2.2.1 Definitions of Mental Workload

Although mental workload has been discussed for more than forty years, there is a lack of commonly accepted definition of mental workload. Literally, mental workload focuses on the activities which are primarily mental (sometimes cognitive) and physical coordination [62]. However, there are few formal definitions of mental workload. Instead, most definitions are more or less operational. Even for those operational definitions, they were from various fields and continued to disagree about its sources, mechanisms, consequences, and measurements [57].

There could be two reasons resulting in the difficulty in getting a clear definition. First, as Wierwille [152] noted, mental workload cannot be directly observed and it only can be inferred from observation. Therefore it is difficult to use single, representative statements to conceptualize mental workload [47]. Second, mental workload can be influenced by numerous factors. In Meshkati's classification [93], those factors can be categorized into two groups: the group of causal factors (including task and environmental variables, operators' characteristics and moderating variables) and the group of effect factors (including difficulty, response and performance variables, and mental workload measures).

Traditionally, mental workload has been defined as imposed task demands, level of performance, the operator's mental and physical effort or the operator's perception [57]. Actually, most operational definitions assume that mental workload is the intersection of a specific operator and the task assigned [57].

Giving a clear unified definition of mental workload is out of the range of this work (more discussion can be found in [22]). For designers, it is quite free to select preferred mental workload definitions as long as the selected ones can help to estimate, assess and optimize their system design. For our work, we take the following definition of mental workload because it represents the cause of mental workload well in our research context:

"*Workload can be defined in terms of the relationship between resource supply and task demand. It is argued that operator workload is directly related to the extent to which the tasks performed by the operator utilizes the limited resources*" [143]

The relationship described in this definition can be illustrated as Figure 2.3. Task performance will break down if the demands excess the available resources. Otherwise, if the available resources are adequate, mental workload is inversely related to reserve capacity. The changes in workload according to this definition may result either from fluctuations of operator capacity or from changes in task resource demands [150].

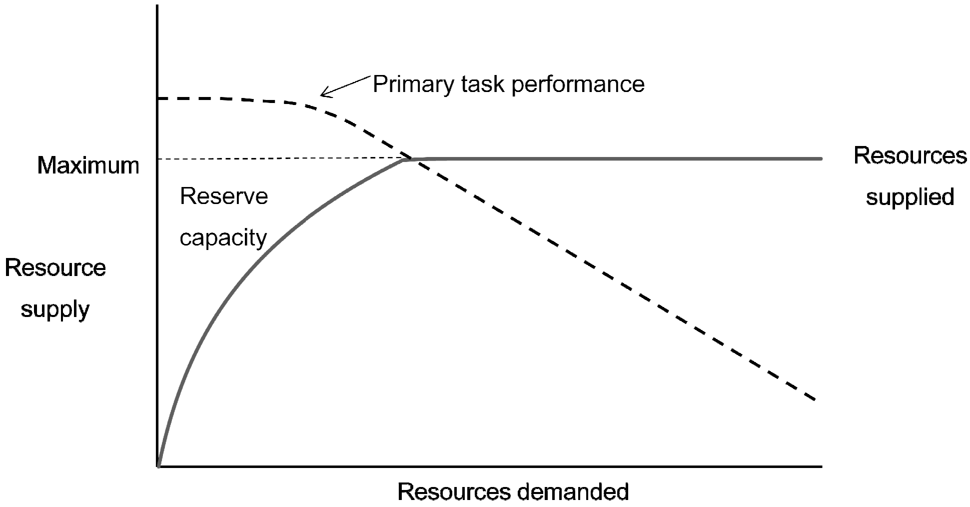

Figure 2.3: Schematic relationship among primary-task resource demand, resources supplied, and performance [150]

2.2.2 Mental Workload Theory: Multiple Resource Theory

Human-computer interaction is fundamentally an information-processing task [123]. The core idea of human information processing is to treat human mind as an information processing device [23]. Many of the workload theories are based on the information-processing model [96].

Based on the concept of multiple processing resources [67, 101], Wickens et al. developed multiple resource theory (MRT) [144, 146-148, 151] which is widely used in human-machine/computer interaction [96, 145-147]. This theory proposes that the mental resources used to perceive information, process information and make a response are multiple and separate. The concept of “resources” connotes something that is both limited and allocatable, while the concept of “multiple” connotes parallel, separate or relatively independent processing [147]. This theory is often represented as the graphical form shown in Figure 2.4.

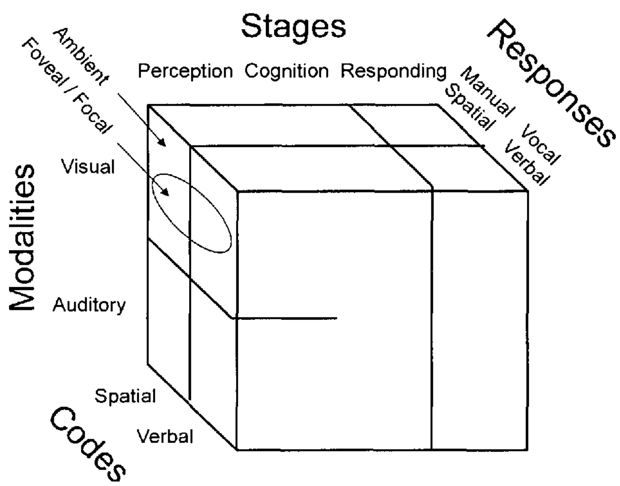

Figure 2.4: The multiple resource model [147]

Early multiple resource theory [148] organized resources into three dimensions: stages of processing (perceptual-central versus response), codes of perceptual and central processing (verbal versus spatial), and modalities of input (visual versus auditory) and response (manual versus vocal). Recently, Wickens [147] introduced the fourth dimension – visual channels (focal or ambient) – into multiple resource model.

Multiple resource theory provides an analytic mechanism to allow system designers/analysts to characterize the tasks by identifying the demands placed on the multiple resources defined by these dimensions. Resource competition will happen if the same pool of resources is required by concurrent tasks. For example, visual attention is shared while driving and reading SMS simultaneously.

A point worth noting is that the competition exists not only between the two tasks requiring the same input modality or same output modality. According to multiple resource theory, the competition can also happen a) between the tasks for similar stages of perceptual/cognitive and response processing; and b) between tasks for similar processing codes.

In order to better predict the relative differences in interference between concurrent tasks, based on previous MRT-related computational models (e.g., W/INDEX [102, 122]), Wickens et al. [145, 147] further developed a computational multiple resource model, which could be seen as the formalization of previous models. In this computational model, each task is represented as a vector for resource demand and task conflict arises if concurrent tasks require the same or related resources. According to the extent of the total demand on both tasks and the extent of conflict for overlapping resources, this model implements an interference formula to predict the performance penalty. Therefore, the total amount of interference between two tasks can be calculated using the following conceptual formula:

Total Interference = Total Task Demand + Conflict

The following components are needed in such a typical model [147]:

- A task analysis shell is used to identify demand levels at different resources on each task.
- A conflict matrix is used to determine the amount of conflict between resource pairs across tasks.
- A computational formula is used to combine total task demand and conflict into an overall interference value.
- A task interference value is provided as the output.
- (Optional) A time line analysis could be used when the particular combination of tasks will be time-dependent.

In our work, we take multiple resource theory as the basis and implement each necessary component mentioned above according to our focus.

2.2.3 Workload Measurement Techniques

As a mental construct, it is quite difficult to directly observe how mental workload changes. Therefore the measurement techniques mentioned in the literature tried to infer the level of mental workload by capturing the change of the operator's psycho-physiological or physiological status or the change of performance.

In the past 30 years, different classifications for mental workload measurement techniques have been proposed and discussed [39, 62, 83, 90, 154]. The most impressive one is the taxonomy proposed by Lysaght et al. [90], as shown in Figure 2.5 in which we explicitly identify the main purpose of the technique – prediction or assessment.

As indicated in the Figure 2.5, the techniques in *Empirical Methods* are often used to gather data (either subjective, physiological, or performance) from human operators [83], while the techniques in *Analytic Methods* can be applied to estimate mental workload in system without operators-in-the-loop [90]. For the purpose of our work, we are more interested in *Analytic Methods* because they can be used to predict human mental workload. Therefore, we then pay more attention to the analytic techniques while briefly discussing the empirical ones.

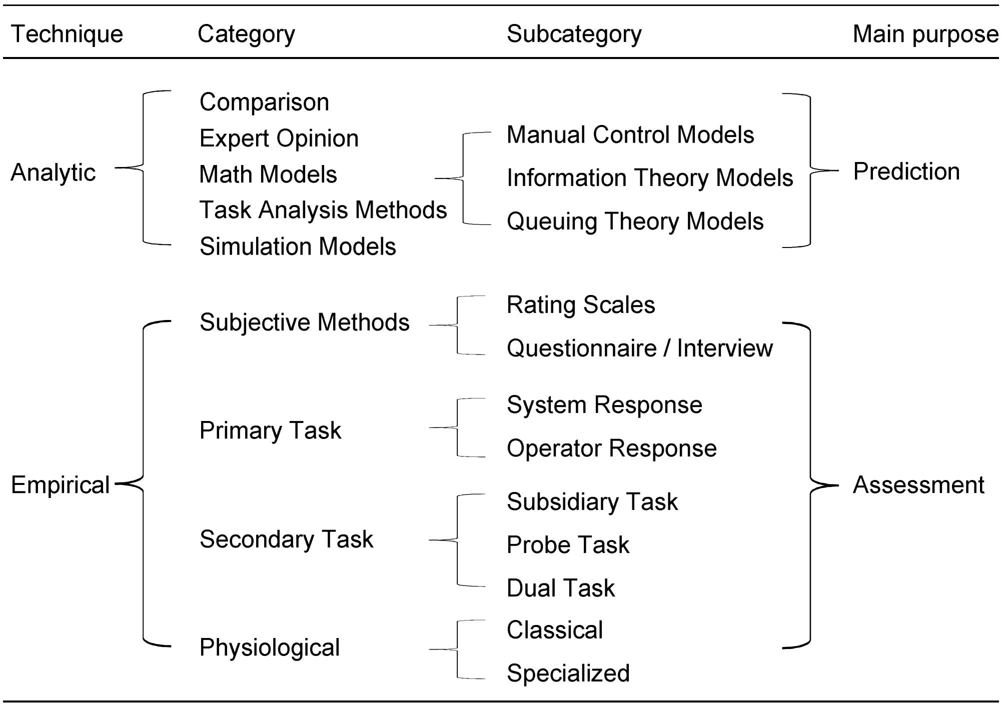

Figure 2.5: A taxonomy of mental workload techniques (derived from [90])

2.2.3.1 Analytic Methods: for Prediction

Analytic methods include five main techniques: comparison, expert opinion, mathematical models, task analysis methods and simulation models. However, in those five techniques, comparison and expert opinion do not use solid models to predict mental workload. Instead, they are grounded in the elicitation of subjective opinions from operators and designers who have direct experience [83]. Therefore, comparison and expert opinion are also called projective techniques and the rest three are also called task-analytic techniques [139]. Math models try to use a combination of series relevant variables to accurately and reliably estimate workload-associated effect on performance but often require very strict environments which limit the use. Besides, there is no clear distinction between task analysis methods and computer simulation models because most simulation models take task analysis as one part [83]. Therefore, for our research, we mainly considered task analysis methods.

Task Analysis Methods

Task analysis is the term applied to any process that identifies and examines tasks performed by humans as they interact with systems [71] and at the core of most work in HCI [36]. Task analysis methods have been widely used to estimate mental workload in preliminary design process. One reason is that they are relatively easy to understand and undertake. More importantly, even if mental workload cannot be estimated, the process of doing task analysis itself still can help designers better understand the system [83].

In order to estimate mental workload, the core work is to identify the indicator of mental workload in the form which can be derived from the variables in the task analysis, such as time utilization [102], resource utilization [2, 102], and busy rate. A number of commonly used models have been discussed in previous literature [83, 90]. Recently, Xie and Salvendy provided a clear summarization including more recent models in [155]. Therefore, subsequently, we mainly discuss the task analysis methods which are more related to our work – VACP (Visual, Auditory, Cognitive, and Psychomotor) [2] and W/INDEX [102].

VACP: Visual, Auditory, Cognitive, and Psychomotor

Based on task resource demand concept [92], Aldrich et al. [2] developed a model known as the VACP model, which can be used in either assessment or prediction. It has four task demand channels: visual, auditory, cognitive and psychomotor.

Visual	Auditory
0.0 No visual activity	0.0 No auditory activity
1.0 Visually register, detect occurrence	1.0 Detect / register sound
3.7 Visually discriminate	2.0 Orient to sound (general)
4.0 Visually inspect / check	4.2 Orient to sound (selective)
5.0 Visually locate / align	4.3 Verify auditory feedback
5.4 Visually track / follow	4.9 Interpret semantic content (speech)
5.9 Visually read (symbol)	6.6 Discriminate sound characteristics
7.0 Visually scan / search / monitor	7.0 Interpret sound patterns
Cognitive	**Psychomotor**
0.0 No cognitive activity	0.0 No psychomotor activity
1.0 Automatic, simple association	1.0 Speech
1.2 Alternative selection	2.2 Discrete actuation
3.7 Sign / signal recognition	2.6 Continuous adjustment
4.6 Evaluation / judgment	4.6 Manipulative adjustment
5.3 Encoding / decoding, recall	5.8 Discrete adjustment
6.8 Evaluation / judgment	6.5 Symbolic production
7.0 Estimation, calculation, conversion	7.0 Serial discrete manipulation

Figure 2.6: An example of VACP scale descriptors

When using this model, a standardized and categorical list in each channel should be derived from the nature of the tasks to show the potential levels of resource demand for each channel. Typically, 8-point scale on each channel is used [2, 11], as shown in Figure 2.6. Then a score is assigned to each channel for each task to assess the resource demand. By adding up all rankings for all tasks, mental workload can be predicted or assessed.

When implementing VACP, evaluators have to be very careful to assign correct levels from the resource channel scales to tasks. Overall, VACP has high validity and diagnosticity. It can be embedded into more complex and specific workload prediction models to estimate resource demand [21, 96].

W/INDEX: Workload Index

W/INDEX (Workload Index) first came into view as a computer-based tool developed by

Honeywell Systems and Research Center [102]. To use W/INDEX, sufficient task information should be provided to three W/INDEX databases: a task timeline, an interface/activity matrix, and an interface conflict matrix. The data flow is shown in Figure 2.7.

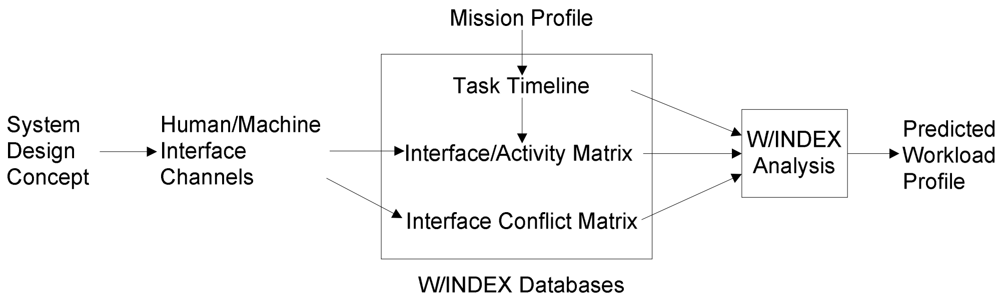

Figure 2.7: W/INDEX data flow [102]

Based on multiple resources theory [148, 151], W/INDEX model first can help designers and analysts assign different resource demand levels (e.g., 0 to 5) to different interface/cognitive channels. Then a very important component known as conflict matrix can be established. Conflict matrix identifies the interference between concurrent tasks in different channels caused by the similarity in the multiple resource space [148].

The core of W/INDEX model is the formula in Figure 2.8 for calculating the instantaneous workload at time T [102]. The first term represents the purely additive workload level, while the second and third ones indicate the penalty due to demand conflicts within channels and between channels respectively [102].

$$W_T = \sum_{i=1}^{l}\sum_{t=1}^{m} a_{t,i} + \sum_{i=1}^{l}\left[(n_{t,i} - 1)c_{ii}\sum_{t=1}^{m} a_{t,i}\right] + \sum_{i=1}^{l-1}\sum_{j=i+1}^{l} c_{ij}\sum_{t=1}^{m}(a_{t,i} + a_{t,j})$$

Where

W_T = instantaneous workload at time T

$i, j = 1..l$ are the interface channels

$t = 1..m$ are the operator's tasks or activities

$n_{t,i}$ = number of tasks occurring at time t with nonzero attention to channel i

$a_{t,i}$ = attention to channel i to perform task t

$c_{i,j}$ = conflict between channels i and j

and

$a_{t,i}$ and $a_{t,j}$ are both nonzero.

Figure 2.8: W/INDEX algorithm

Later, in order to adequately identify the resource conflict between tasks, a modified W/INDEX model was proposed by Sarno and Wickens [122], as shown in Figure 2.9. In this modified form, the number of terms is reduced from three to two, which represent within tasks demand and across tasks interference separately. The former is an estimated value of total resource demand of all tasks by assuming no conflict between tasks so it also can be seen as total resource demand [145, 147]. The latter represents the penalty caused by interference between tasks.

$$W_T = \sum_{i=1}^{6}\sum_{t=1}^{M} a_{t,i} + \sum_{i=1}^{6}\sum_{j=i}^{6}\sum_{t=1}^{M-1}\sum_{s=t+1}^{M} c_{ij} \times f\left(a_{t,i}, a_{s,j}\right)$$

Where

W_T is the total workload value

$a_{t,i}$ is the attentional demand to channel "*i*" due to task "*t*"

c_{ij} are interference coefficients characterizing the additional load imposed by two tasks competing for common resources

i,j are indices of the six interface channels: visual input, auditory input, spatial cognition, verbal cognition, vocal output and physical output

t,s are indices identifying one of "*M*" active tasks

$f(a_{t,i}, a_{s,j})$ is a function that assumes a value of "$a_{t,i}+a_{s,j}$" if both attentional demands are nonzero but it assumes a value of zero if either attentional demand is zero

Figure 2.9: Modified W/INDEX algorithm

2.2.3.2 Empirical Methods: for Assessment

Empirical methods are widely used for mental workload assessment [90, 148, 150]. These methods gather data from operators so operators have to participate in designed empirical studies. For our work, in order to assess the quality of mental workload prediction, it is necessary to compare the predicted results with data gathered by using empirical methods. In this section, we first briefly discuss the most commonly used empirical methods. Then we focus on one of the most popular subjective method – NASA TLX [51] which is adopted in our work.

Overview for Empirical Methods

Commonly used empirical methods are: performance-based workload measures (both primary task measures and secondary task measures), subjective measures and physiological measures.

In *Primary Task Measures*, the task performed with the system is referred to primary task. Performance on the primary task is measured as the indicator of mental workload. Although primary task measure is not really mental workload measure per se, it does reflect the change of mental workload in the form of performance degradation. Intuitively, primary task measures are ease-of-implementation and can be accepted by operators. However, as indicated in [150], this kind of measures cannot discriminate the two tasks both with sufficient reserve capacity, cannot guarantee the consistence between the measurements in different primary tasks, cannot always obtain good measures of primary task performance and can be limited by user data.

Secondary Task Measures assume that the primary task takes a certain amount of cognitive resources so the reserve capacity can be measured to reflect mental workload. In secondary task measures, operators are asked to perform the primary task and the secondary task simultaneously. By changing the difficulty of the primary task, the performance on secondary task will be affected. The shortcoming of secondary task measure is that it often seems artificial, intrusive, or both for operators performing the tasks [149].

Subjective Measures are probably the most common methods used to assess mental workload. Those measures use operators' self report of experienced effort or capacity expenditure to formalize mental workload levels. Direct or indirect questionnaires with single or multiple subjective scales are used to collect operators' opinions [94]. Typically, those operators' opinions are easy to obtain but it is hard to guarantee that operators' subjective reports always coincide with their performance [4].

Physiological Measures are also widely used in mental workload assessment. The changes of mental workload can be accompanied by the changes of human physiological process such as nervous system activity. As a result, mental workload can be evaluated by measuring appropriate physiological variables such as heart rate variability. Compared to secondary task measures and subjective measures, extra operations beyond the primary task are not needed in physiological measures. However, the equipment and instrumentation required may limit the usefulness [149].

Category	Example Techniques	Description	S	C	E	D
Primary Task	Reaction time	The time starting from when stimulus is presented to when a response is executed.	M	L	M	L
	Accuracy	The form of percentage or proportion of errors	L	L	M	L
Secondary Task	Time estimation	The estimation reported by the operator about how much time has elapsed.	M	M	L	M
	Probe reaction time	The reaction time for a stimulus unrelated to the primary task appears periodically.	M	M	L	M
	Memory search	A task in which the operator is required to indicate whether the probe item is present in or absent from the memory set.	M	M	L	M
Subjective	Modified Cooper Harper scale	This scale consists of a 10-point scale with a decision-tree format.	H	L	L	L
	SWAT	It's a multidimensional rating scale with three subscales – time load, mental effort load and stress load.	H	L	L	H
	NASA TLX	It measures workload from six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration Level.	H	L	L	H
	Workload profile	It's a multidimensional instrument based on multiple resource theory.	H	L	L	H
Physiological Methods	Visual scanning	The direction of pupil gaze can be used to assess mental workload.	H	H	H	H
	Heart rate variability	The power at 0.1Hz, determined by spectral decomposition of the HRV data, is a good measure of mental effort	M	M	M	M
	Pupil measures	Pupil correlates quite closely with the resource demands of a large number of diverse cognitive activities.	M	H	M	M
	Event-related potentials	ERPS are measures of the brain activity that follows presentation of a signal.	M	H	H	H

S – Sensitivity, C – Cost, E – Effort, D – Diagnosticity

L – Low, M – Moderate, H – High

Table 2.6: Summary for commonly used empirical methods (derived from [90])

Table 2.6 (derived from [90]) lists the typical techniques used for each method. Besides briefly explaining each technique, we emphasized the following properties: sensitivity, cost, effort and diagnosticity. For our work, considering those four properties, subjective measures are suitable because they provide good sensitivity, relatively low cost and effort with fair diagnosticity. More specifically, NASA TLX [51] has been widely used to assess mental workload in mobile HCI and can be a good method for our research. Therefore, in subsequent section, we review NASA TLX in details.

Selected Subjective Assessment Measure: NASA-TLX

Based on the assumption that workload is a hypothetical construct that represents the cost incurred by a human operator to achieve a particular level of performance, NASA TLX (NASA Task Load Index) was proposed by Hart et al. [51]. This method emphasizes the external characteristics of mental workload. According to the conceptual framework in [51], workload emerges from the interaction between the requirements of a task, the circumstances under which it is performed, and the skills, behaviors, and perceptions of the operator. Therefore, NASA TLX measures mental workload from the following six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration Level, as shown in Table 2.7.

By asking participants to give NASA-TLX scores, a mean overall mental workload score can be calculated for each dimension. In order to identify the weight of each dimension in the mental workload, researchers suggested that participants need to make simple decisions about which member of each paired combination of the 6 dimensions is more related to their personal definition of workload [49], which is called weighted NASA

TLX. However, high correlations between unweighted and weighted NASA TLX workload scores have been shown [20, 99, 105].

Title	**Endpoints**	**Descriptions**
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Table 2.7: The NASA TLX rating scale definitions [51]

Due to the ease of use, NASA TLX has been used in a variety of fields [51]. In mobile HCI, it has been widely used in the evaluation of mobile interactive technologies specifically on the investigation of the influence of interactive technologies on mental workload. For example, Brewster [16] used NASA TLX to explore mental workload while using multimodal technologies to overcome the lack of screen space on mobile devices.

2.2.4 Mental Workload in Mobile HCI

For mobile HCI designers, studying mental workload is important due to the following two fundamental reasons. First, although the relationship between performance and mental workload is not simple and clear, the operator and system performance still can be quantified by evaluating the mental cost of performing tasks [22]. More specifically, as Lysaght et al. [90] asserted, “One goal of workload research is to predict impending room – failure of performance”. Second, performance is not all that matters in the design of a good system and mental workload can be used when performance measures are not enough to assess the system design [22, 150]. For example, similar performance on different system design choices but with different levels of mental workload could be observed.

Studying mental workload in mobile HCI is also driven by limited resources usage and multitasking environments.

For human operator, the cognitive resources which can be used for performing tasks are not infinite [150]. The input and output hardware of mobile devices, such as the small screen, further limits the use of limited cognitive resources. Recently, there are increasing interests in extending input (e.g., using hand gestures[116]) and output (e.g., using haptic feedback [88]) modalities for mobile interaction. In order to adequately leverage kinds of cognitive resources to avoid the lack of specific resource (e.g., visual attention) in mobile interaction, multimodal techniques have been explored [60, 61]. However, it is still challenging to design such techniques which can really help users finish tasks with acceptable resource consumption.

On the other hand, mobile interaction often takes place in multitasking environments. For example, many drivers use mobile phones while driving. According to multiple resource theory, resource competition could happen while performing multiple tasks simultaneously [147, 148]. It will cause the increase of mental workload in some or all tasks. Therefore, for mobile HCI designers, it is also important to make sure that their design can work well in potential multitasking environments.

For mobile HCI designers, mental workload is an indicator which can reflect the use of cognitive resources in their design. Based on the understanding of the mental workload in their design, mobile HCI designers can optimize the design to get optimal workload which refers to a situation in which the user feels comfortable, can manage task demands intelligently, and maintain a good performance [50].

Currently, mental workload assessment has been widely accepted and used by mobile HCI designers in evaluating the usability of kinds of mobile interactive technologies such as mobile text entry (e.g., [89, 97, 156]), and indoor/outdoor navigations (e.g., [45, 100]). Among the different kinds of assessment methods, the most common one used in mobile HCI is NASA TLX [51] and its variants. For example, in order to capture the influence on mental workload of irritation caused by tactile feedback in their system, Hoggan et al. [54] added an extra factor – annoyance – to the original NASA TLX.

In addition to workload assessment in designs, only a few researchers attempted to explore the nature and alternative measurement of mental workload for mobile HCI. Most of them are fragmented and less systematical. For example, Sá and Carriço [121] proposed that mental workload should be discussed as scenario variable in the early stage of mobile applications design. Mizobuchi et al. [97] investigated the possibility of using walking speed as a secondary task measure of mental workload for mobile text entry. One of the most influential work was done by Oulasvirta et al. [110]. Building on multiple resource theory, they proposed the Resource Competition Framework to explain how psychosocial tasks typical of mobile situations compete for cognitive resources. This competition was observed to consume attention resources thereby causing less fluid interaction, which actually reflects the change of mental workload.

2.2.5 Summary

Mental workload is defined in terms of the relationship between resource supply and task demand [143]. In multitasking situations, this relationship is expressed as a competition for cognitive resources. Multiple resource theory [147, 148] provides a view to understand how cognitive resources are consumed and shared by concurrent tasks. In the past four decades, different kinds of mental workload measurement techniques have been developed. Workload prediction methods especially task analysis methods such as VACP [2] and W/INDEX [102] have been widely used in human-machine/computer interaction for modeling and predicting mental resource competition in multitasking situations such as driving [55] and piloting [102]. However, as a typical case of multitasking situation, there is a lack of systematic investigation of mental workload prediction in mobile HCI.

The differences between our work and previous work are listed as follows:

- Firstly, unlike the research on mental workload, our goal is not to develop new fundamental mental workload theories but to adapt existing mental workload theories and prediction methods in mobile HCI.
- Secondly, unlike the work involving the study on mental workload in mobile HCI, our work focuses on mental workload prediction rather than mental workload assessment. As discussed above, for mobile HCI designers, in order to improve the usability of mobile interactive technologies by optimizing users' mental workload, workload assessment has been widely accepted and used in the evaluation phase. However, mental workload prediction has not been paid enough attention in mobile HCI.
- Lastly, our pursuit is not only the adaptation of mental workload prediction but also the simplification of mental workload prediction. Traditional mental workload prediction methods require high expertise, but our work tries to provide a relatively simple way to help mobile HCI designers predict users' mental workload in the early design phase.

Chapter 3

Exploring User Motivations for Eyes-free Interaction on Mobile Devices

In this chapter, we present a user-centered exploration of user motivations in choosing eyes-free technologies for mobile interaction. To assure a wide range of user feedback, we held four focus groups with twenty-two participants in total and identified ten typical user motivations for eyes-free interaction, classified into four categories (environmental, social, device features, and personal) as defined by the intersection of two dimensions (contextual vs. independent; physical vs. human).

3.1 Methodology

In order to collect user motivations for eyes-free interaction in an open-ended fashion, we chose to use focus groups, which are particularly suitable for early exploration in identifying new problems and assessing users' needs [98].

3.1.1 Participants

Twenty-two participants (indexed P1-P22; 13 male and 9 female) from a diverse background (14 students from different disciplines: computer science (8), biology (3) and Chinese studies (3), 8 working professionals from different industries: banking (1), telecommunications (4), education (2), and IT (1)) were recruited for our focus groups. Average age was 26.7 years (SD=7.40). All participants had more than 5 years of experience in using mobile devices. Each focus group had 5 or 6 participants.

3.1.2 Procedure

Four focus groups were conducted. Each of them lasted approximately 90 minutes with the following five steps:

- Firstly, the moderator introduced the purpose of this research. (~5 mins);
- Secondly, the moderator introduced the concept of “eyes-free” with the demonstration using two tasks: volume change in HTC G2 and text typing in Dopod C750 (~5 mins);
- Thirdly, participants performed a self-introduction and discussed their first impression of eyes-free interaction (~15 mins);
- Fourthly, in the main discussion participants freely discussed three themes: a) situations where visual interaction is not suitable, b) experience of using eyes-free interaction and c) expectations of eyes-free technologies (~1 hour);
- Lastly, the moderator summarized and did a debriefing (~10 mins).

3.1.3 Analysis

Each focus group was filmed; the recordings were transcribed and coded based on the Grounded Theory [131] by the two experimenters. The following measures were taken to minimize the influence of less logical statements that often occur in focus groups towards the validity of motivation categorization: 1) Participants were encouraged and guided by the moderator to reflect on and verbalize the underlying logical meaning behind their statements; 2) During the coding phase, less logical statements that were not backed up by other statements were not used as evidence.

3.2 A Categorization of Motivations

Via clustering and merging, ten motivations for using eyes-free interaction in mobile context (identified as M1 to M10) emerged from the focus groups. We identified the properties of each motivation and found that they were related to specific settings and originated in either the physical or human realm. Based on this observation, the ten motivations were categorized along two orthogonal dimensions as shown in Table 3.1.

	Physical	Human
Contextual	***Environmental*** **M1**: Enable operations under extreme lighting conditions (e.g., [16]) **M2**: Improve safety in task-switching (e.g., [16])	***Social*** **M3**: Foster social respect (e.g., [8]) **M4**: Avoid interruption to social activities (e.g., [8]) **M5**: Protect private information (e.g., [81])
Independent	***Device Features*** **M6**: Enable operation with no/small screen (e.g., [157]) **M7**: Enable multitasking on same device (e.g., [81])	***Personal*** **M8**: Entertainment **M9**: Serve desire for self-expression **M10**: Lower perceived effort

Table 3.1: Categorization of user motivations for using eyes-free interaction: based on two dimensions (contextual vs. independent; physical vs. human) we sorted all motivations into four categories (environmental, social, device features, and personal)

The first dimension is the context dependency, which can be either contextual or independent. The second dimension is the realm, which can be either physical or human. Crossing these two dimensions results in four categories: environmental, social, device features, and personal. Now, we present, examine, exemplify, and discuss the ten motivations (M1 to M10) by category.

3.2.1 Environmental (contextual + physical)

In many environments interaction with mobile devices is interfered with or prevented by the characteristics of that environment.

As participants indicated, extreme lighting conditions are a major source of interference to visual perception (M1) [16], which can be either too bright or too dark. In the former situation, participants complained that overly bright situations, such as direct sunlight, often make the screen unreadable, "*It is hard for me to read the text while walking in bright light. So I have to try to find a place without so much light*." (P3) In the latter situation, one participant mentioned her experience when working in a dark room for film development: "*I often needed to answer calls or wanted to switch the music, but I was developing photographs in a dark room where the light from the screen was not allowed*." (P5)

Another motivation frequently mentioned is improving safety in contexts where switching visual attention between the device and the physical environment poses safety concerns (M2) [16]. For example, it is hazardous to switch visual attention between a mobile device and the road while driving. Nonetheless, such simultaneous usage is often unavoidable: "*Everyone knows it is dangerous to use mobile phones while driving, but I just want to use it. I think it is a part of my life.*" (P8)

3.2.2 Social (contextual + human)

As indicated by Palen et al. [111], using mobile devices has become a part of social norms. However, in some situations overtly using a mobile device is socially inappropriate (M3 and M4), while some other situations raised privacy concerns (M5).

In some social settings, openly interacting with mobile devices is unanticipated and sometimes unacceptable. For instance, while talking with others, frequently playing with mobile phones is impolite and may leave a bad impression on the other party. Nonetheless, sometimes attending to the mobile device is necessary (e.g., an urgent message). In that case, users can be motivated to use eyes-free interaction to reduce the perceived interference between mobile interaction and the surrounding social activities to maintain social respect (M3) to others [8], "*When I was doing a presentation, a phone call came and I felt the vibration. I couldn't take it out because it was impolite. So I just reached into the pocket and pressed the end button.*" (P10)

In other situations, users may voluntarily desire to pay more attention to the surrounding social activity, such as when attending a lecture. In that case, avoiding the interruption to the social activities (M4) can motivate users to adopt eyes-free interaction [8]. For example, one participant described such a situation where eyes-free interaction can facilitate quick responses – "*I often text messages in class. But in math class, sometimes I had to copy the formulas written by the teacher so that I couldn't pay attention to the received messages. So sometimes I missed some appointments.*" (P3)

Besides maintaining social relationships, users may also be motivated to use eyes-free interaction for protecting privacy. More specifically, interaction relying on visual feedback has the danger of leaking private information to others in social contexts (M5) [81]. Eyes-free interaction is expected to reduce this risk by hiding the user input (e.g., the operation of pressing buttons) and/or the device output (e.g., displayed visual information). As one participant indicated, "*I am always worried that my password could be seen by others when I am in a queue.*" (P11)

3.2.3 Device Features (independent + physical)

Sometimes, users would like to use eyes-free interaction with their mobile devices due to the physical constraint of the devices themselves. In order to overcome inconveniences (M6 and M7) caused by device constraints, users are motivated to adopt eyes-free interaction.

Participants mentioned two types of inconveniences related to eyes-free interaction on mobile devices. On one hand, devices designed with small or even no screens (M6) make interaction using visual feedback difficult and/or irrelevant [157]. For example, "*There is no screen on my iPod shuffle. But I can operate it very well just with the audio feedback.*" (P2) On the other hand, interruptions can happen while performing multiple tasks on the same mobile device (M7) [81], which can motivate users to use eyes-free interaction to reduce the interruption: "*When talking with my customers on the phone, I have to frequently check my schedule in my phone to make appointments. So I have to frequently suspend the phone conversation to look at the screen. It is very inconvenient.*" (P20)

3.2.4 Personal (independent + human)

In addition to achieving practical goals, eyes-free interaction is also motivated by personal factors. In this category, the motivations (M8, M9, and M10) are more intrinsic to the users themselves and not necessarily dependent on devices or contexts.

Some participants indicated that they would like to use eyes-free interaction just because they thought it was fun to use (M8). The joy is generated from the unusual experience and the resulting sense of accomplishment. As one participant said, "*I can experience very different things when I am using eyes-free interaction. I think I am very good if I can succeed.*" (P17)

Several participants also indicated that their desires for self-expression (M9) made them take the initiative to use eyes-free interaction. One participant said, "*It is cool to show my friends that I can use my phone without using my eyes. I think they envied me and I felt proud.*" (P10)

Interestingly, participants mentioned that sometimes they used eyes-free interaction even when it was possible to visually focus on the mobile devices. An underlying reason may be that some users perceived the cognitive/physical effort for eyes-free interaction (M10) to be lower than for visual interaction. For example, one participant mentioned, "*When I enter the library, I need to switch my phone to silent mode. But it is troublesome to take the phone out. So I like to do it in my pocket without looking at the phone.*" (P4)

3.3 Discussion

Although our investigation has covered a variety of different motivations, this is meant to be a list of representative motivations instead of an exhaustive one. We expect the categorization suggested will help to identify more user motivations in the future. Still, we believe this list provides a solid initial basis for discussion of design insights for the diversity of motivations, the concurrency and shifting of motivations, and related design implications.

3.3.1 Diversity of Motivations

Our results have shown that there is a diversity of motivations for eyes-free interaction, ranging from environmental constraints to personal intentions. Designing a single eyes-free solution to cover all those motivations is challenging and perhaps undesired, but it is essential for designers to be aware of this diversity. Much research has focused on eyes-free interaction widgets, which are more or less designed as a general technique (e.g., earPod [157]). However, in order for such inventions to be widely adopted by users, mechanisms to adapt and customize them to various user motivations may be key.

By exploring the diversity of motivations, we also surprisingly find that personal intentions may play an important role in motivating eyes-free interaction. On one hand, this reveals future potential innovations such as the design of eyes-free systems for entertainment. On the other hand, perhaps more significantly, it highlights the role of enjoyment when designing eyes-free interaction.

3.3.2 Concurrency and Shifting of Motivations

It is important for designers to understand how multiple motivations can play a joint role. That is, frequently a small number of motivations are not independent and may all be in effect concurrently during an activity.

In our study, concurrency of motivations is observed in two aspects. First, as a kind of basic demand, it is quite common for users to mix M10 together with other motivations.

For example, participants who reported to be in outdoor environments with bright sunlight also complained that the small screen influenced their operations and that they expected eyes-free interaction to require less effort.

"*Sometimes when I am walking (M2) in bright daylight (M1), I have to search for someone's contact information in my phone. I have to make too much effort (M10) to recognize the text in the small screen (M6).*" (P19)

Second, if the user is in a specific context, different motivations related to the contextual dimension often complement one another. For example, in social activities, the need to avoid interrupting social activities often complements the need to foster social respect.

"*My friend was supposed to present at a seminar. But he was late and his professor asked me about his whereabouts, I wanted to send a message to get my friend to contact his supervisor immediately. But I had to focus on the chat with the professor (M4) and I didn't want to be rude (M3).*" (P8)

Besides the concurrency of motivations for the same user and device, there are cases when the user, while attempting to complete a task, is exposed to different situations consecutively, each of them requiring eyes-free interaction but with different motivations, which we call "shifting". For example, as one participant mentioned, "*When I am driving, typing text may be dangerous (M2). But after I arrive at the destination and talk with others, typing text could be impolite (M3).*" (P14) In both situations, the task was the same (typing text), and both had the need for eyes-free interaction, but the motivations were different (M2 vs. M3).

3.3.3 Design Implications

Based on the observations and analysis of user motivations, we highlight three groups of implications for the design of eyes-free interactions in mobile usage.

Make the interaction method adaptive to changing motivations: As discussed above, the user may want to use eyes-free interaction with different motivations at different times. In this case, a single interaction method may not satisfy different motivations unless dynamic adaptation occurs. We notice that motivations often vary together with changes in the contextual settings. So designers could leverage context-aware technologies to facilitate such adaptive interaction methods. For example, by detecting the change in contextual settings, non-visual reminders could change from vibrations in a meeting room (e.g., M3 and M4) to audio cues while driving a car (e.g., M2).

Seamlessly integrate with social activities: During social activities, eyes-free interaction demands more social responsibility (e.g., M3, M4, and M5). So designers need to think about the social impact of interaction methods they design for eyes-free interaction. Ideally, eyes-free interaction should be subtle and socially acceptable. One possible solution is embedding eyes-free interaction into commonplace objects and socially acceptable behaviors such as rotating a finger ring [8].

Minimize cognitive/physical workload: Although eyes-free interaction reduces reliance on visual attention, it is still possible to cause a high cognitive/physical workload due to the uses of cognitive/physical resources from other modalities [138]. Thus, designers need to carefully design the interaction method so that users can finish the eyes-free interaction with a minimal cognitive/physical cost. Beyond the desire for perceived convenience (e.g., M10), it is also relevant to more critical issues such as safety (e.g., M2).

Chapter 4

Exploring Mental Workload Prediction in Mobile HCI Design

Previous work (e.g., [21, 96]) have already shown that in practice predicting mental workload is a work integrating different theories and models. Modifications in applying those theories and models are often necessary according to the different situations. For most mobile HCI designers, mental workload prediction is a challenging work due to the requirement of expertise. Besides adapting workload prediction methods to mobile HCI fields, another important goal of this work is to help mobile HCI designers use workload prediction in an easier way. Therefore, inspired by user-centered design [1], we attempted to involve users in this process.

In this chapter, we first introduce the mental workload prediction method tailored from computational multiple resource theory. Then we present the empirical study for validating our tailored method. We then briefly discuss the possible simplification for our tailored mental workload prediction method. In closing, we summarize and show some notes about applying our tailored prediction methods.

4.1 Mental Workload Prediction Method

In this section, we first analyze and identify the common cognitive resources in mobile HCI tasks based on multiple resource theory. Then we show our tailored mental workload prediction method for mobile HCI.

4.1.1 Analysis for Cognitive Resources in Mobile HCI

Multiple resource theory [147] uses four dimensions – stages, codes, modalities and responses – to divide the cognitive resources. Following the stages of human information processing (perception, cognition and responding), we identify five different cognitive resources commonly used in mobile HCI, as shown in Figure 4.1. Although there could be more cognitive resources (e.g., Oulasvirta et al. defined ten cognitive faculties with different cognitive resources in [110]), the selected cognitive resources are representative and it is necessary for deep analysis to keep a minimal set. Subsequently, we give a detail description of each resource following the stages of human information processing.

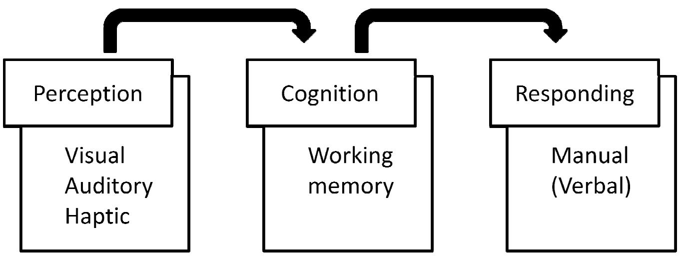

Figure 4.1: Cognitive resources for mobile HCI in three stages: perception, cognition and response

4.1.1.1 Perception

In the perception stage, the information is sensed and then provided a meaningful interpretation. The cognitive resources consumed in mobile interaction in this stage are mainly related to visual, auditory and haptic resources.

Visual resources are used to search, select, integrate and perceive visual stimuli. In traditional mobile HCI, visual interaction is dominated. The information is given in the form of specific visual stimuli such as texts, images and videos and then the user perceives the information through visual channel. However, in many scenarios, visual resources are consumed not only by mobile HCI tasks (e.g., typing a message) but also by contextual tasks (e.g., driving a car).

In the interaction with mobile systems, besides visual stimuli, auditory stimuli are also commonly used too. With the exception of phone conversations (typically we do not treat them as HCI tasks), audio cues (speech or non-speech) have been widely used for information presentation in mobile HCI tasks. For example, Li et al. [81] replaced traditional visual in-call menu of a mobile phone with speech. Researchers also created auditory icons [43] and earcons [13] to help the expression of information in the form of audio cues.

Recently, haptic channel is paid increasing attention in mobile HCI. Haptic perception refers to the process of recognizing objects through touch and force senses. The resources in this channel are used to search, select, integrate and perceive haptic stimuli. In mobile HCI, those resources are required by leveraging the physical tactile properties or vibro-actuators. For example, the feedback of interaction with touch screen can be enhanced by using vibro-actuators [136]. By adjusting vibration parameters, information can be encoded in a special form called Tactons [15].

4.1.1.2 Cognition

In the cognition stage, cognitive operations such as rehearsal, reasoning, or image transformation are carried out. According to human information processing [150], working memory plays an important role in those operations. Working memory refers to a brain system that provides temporary storage and manipulation of the information necessary for cognitive operations [9]. In Baddeley's model [10], working memory consists of three components: a central executive component and two "storage" systems – the visuaospatial sketch pad for analog spatial information and phonological loop for verbal information in an acoustical form.

The use of working memory is mainly limited by the capacity and time. Researchers have found that the capacity of working memory is around 7±2 chunks of information [95], where a chunk is the unit of working memory space. The other limit is caused by how long information may retain and it also affects the capacity of working memory. Therefore, in human-computer interaction, an important principle is to minimize both the time and the number of chunks of information users have to keep. Especially in mobile interaction, users are often in multitasking situations sometimes with temporal tensions [132] so the effective use of working memory is crucial.

In our work, we treat working memory as an integral component and shared by different cognitive operations.

4.1.1.3 Responding

In the responding stage, users select proper response and execute the selected response. The cognitive resources in this stage are used to sequence, time, control and finalize kinds of motions. In mobile HCI, the response given by users is often in the form of verbal control or manual control.

Although verbal control is more or less supported by mobile devices especially mobile phones (e.g., Siri in iPhone 4S [5]), even without considering the accuracy of voice recognition, the use of voice control is limited in most mobile scenarios especially in public scenarios [44]. Therefore the major responding method in mobile HCI is still manual control. While being required to response the mobile system (e.g., selecting the menu item), specific manual operations are performed. In the early time of mobile devices, these operations are performed by pressing specific physical buttons or using a stylus. Recently, with the development and application of touch-based surface, direct-touch finger gestures are becoming more and more popular. For example, Pirhonen et al. [113] proposed five gestures (four sweeps and one tap) and evaluated them to show the usability of gestural metaphors. Body movements with bigger rang such as hand shaking [153], wrist rotation [109] and head nodding [16] are also leveraged for manual responses.

In this work, we only take manual control as the representative form in the responding stage because it is more general.

4.1.2 Resource Competition: Mobile HCI Tasks vs. Mobile Scenarios

Mobile interaction often occurs in specific mobile scenarios such as walking in a street or driving a car as mobile devices are originally designed for mobile purposes. Users are expected to use mobile devices in different mobile scenarios where users often have to deal with kinds of contextual events. The influence of mobile scenarios is multifaceted. According to Goodwin and Duranti [46], users' actions can be affected by four basic contextual parameters: the setting (social and spatial framework), behavioral environment, linguistic and extrasituational context. The most direct impact of mobile scenarios is to greatly enhance the requirements of multitasking. For example, when using a mobile phone while walking, besides interacting with the mobile phone, the user has to keep walking by planning routes, avoiding obstacles and so on.

However, the available cognitive resources are limited. While the limited resources are shared by different tasks from the interaction with mobile devices and the events in scenarios, resource competition is raised. In this case, for each involved task, the resource supply does not always meet the task demand, thereby causing high mental workload. Therefore, a good mobile HCI design should avoid or reduce the resource competition between mobile HCI tasks and mobile scenarios so that a relatively low mental workload can be maintained. By predicting mental workload for mobile HCI tasks in mobile scenarios it can at least help designers identify and avoid "bad" designs in the process of coming up with "good" designs.

In the current stage of our work, we do not consider multitasking situations with two or more simultaneous mobile HCI tasks (e.g., using two mobile devices simultaneously). When referring to task interference, we always refer to the interference caused by the resource competition between mobile HCI tasks and mobile scenarios.

4.1.3 Our Tailored Prediction Method

According to the components defined in [147] for a typical computational MRT-based model, we used a similar four-step method, as shown in Figure 4.2.

In step 1, for each given mobile HCI task and scenario, the resource demands should be identified first. Previous researchers intended to invite human factor/design experts to perform this activity. However, in our method, the decision is left to users. In step 2, resource conflict between the mobile HCI task and corresponding mobile scenario is analyzed based on the conflict matrix proposed by Wickens [147]. In step 3, a algorithm is used to calculate the total potential interference between the mobile HCI task and corresponding mobile scenario. In this step, the modified W/INDEX algorithm [122] is used. The main work is thus done in the first three steps. However, we still want to remind designers that the purpose of mental workload prediction is to predict the change of mental workload in real situations so that they can improve their designs. That is why step 4 is added into this method. In the subsequent sections, each step is introduced in details.

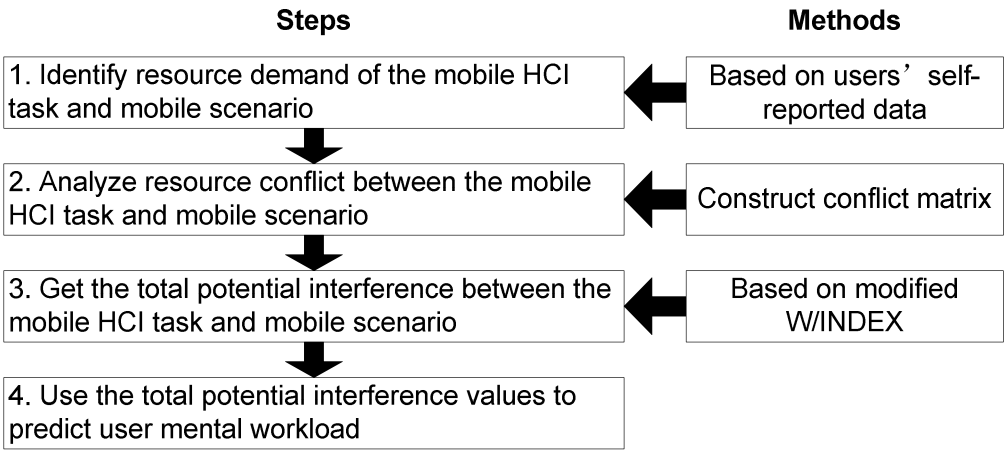

Figure 4.2: The process of mental workload prediction method

4.1.3.1 Identify Resource Demand

Based on the separate resources defined in multiple resource model (as discussed above, those resources are visual, auditory, haptic, working memory and manual resources), a demand vector is generated to represent the resource demand of each task. In this vector, the demand level of each resource is represented by a single number (e.g., 1 for some demand and 0 for no demand). Figure 4.3 shows an example of demand vector for a sample task.

	Visual	Auditory	Haptic	Working Memory	Manual
Task A	1	0	1	1	0

Figure 4.3: An example of demand vector (1 for some demand, 0 for no demand)

Although it seems simple, identifying demand vectors often requires the designers/analysts to have the expertise about human factors and related methods (e.g., VACP [2]). In actual fact, the value of each demand level of each resource is an estimate. The accuracy of this estimation heavily affects the mental workload prediction because the prediction is based on this estimation. However, for most mobile HCI designers (e.g., independent Apple application developers), it is challenging to identify the demand vector of each task as accurately as possible.

Therefore, in our method, we take users' self-reported data into account to help this process. More specifically, the responsibility of identifying resource demands is assigned to users. For the designs to be assessed, a certain number of users (typical not less than 5) are invited to get an experience about the related tasks (using prototypes or just design specifications) which can cover the design issues. Then by finishing a questionnaire, which lists all resources and corresponding optional demand levels (e.g., 0 for no demand and 5 for full demand), users report the perceived demand level of each resource in each task. Figure 4.4 illustrates a sample question for self report. The average value of all users' perceived demand levels is used for the corresponding resource in the final demand vector. Lastly, the resource demand of each task is calculated by summing up each demand level for each resource of this task, as Sarno and Wickens did in the modified W/INDEX algorithm [122]. For example, if the demand vector for task A is (1, 2, 3, 4, 0), then the resource demand for this task is 1+2+3+4+0=10.

1. How much visual attention did you pay to the task?
(Does the task require you to look at something? If so, how much do you need to concentrate on it? 0: I don't need to pay visual attention to it at all. 5: I can't switch my attention at all and I need to pay full attention to this task)
(no demand) 0 1 2 3 4 5 (full demand)

Figure 4.4: A sample question for self report

There are two main advantages of using users' self-reported data. Firstly, to a large extent, users' self-reported data can help designers with little or no expertise to perform resource identification in a relatively higher accuracy compared to one without it. Collecting users' self-reported data also benefits expert designers as they will be able to identify the resource demand value of each task with a higher degree of confidence. Secondly, self-reported data can provide a different view for designers to see how users perceive their designs and help to address any potential design problems in this process.

4.1.3.2 Analyze Resource Conflict

Resource conflict between two concurrent tasks is analyzed by using a conflict matrix, which determines the amount of conflict between resource pairs across tasks. Ideally, if two concurrent tasks cannot share a given resource, the conflict value is 1. If two tasks can perfectly share the given resource, the conflict value is 0. Therefore, all conflict values are bounded between 0 (no conflict) and 1 (maximum conflict).

In our method, a symmetric matrix is used, as shown in Table 4.1. The conflict values in this matrix are based on a set of heuristic values and simple rules proposed by Wickens et al. [55, 145, 147]. In order to make it more suitable for mobile HCI conditions, some necessary changes are made and briefly described as follows.

First, instead of using 0, a baseline conflict value of 0.2 is assumed because concurrently performing two tasks always leads to some cost of concurrence. Therefore, all values in the conflict matrix are non-zero. Second, we assume that concurrent demand for different perceptual resources in two tasks does not increase too much conflict so the baseline conflict value is enough to identify the corresponding conflict. Third, those cells on the negative diagonal (defining identical resources between two tasks) involve the greatest conflict. However, the conflict values are still less than 1 because it is still feasible for two tasks to share the same resource (e.g., visual channel) not perfectly. The value will be 1 only in one case where voice responses are concurrently required by two tasks. Fourth, since working memory is treated as an integral part in this study, we assume that the ability of doing concurrent tasks will be affected if working memory and certain perceptual resource are required concurrently. In that case, we increased the conflict value between working memory and concurrent perceptual resources to 0.4. Fifth, we also assume the concurrent requirements of manual response and haptic perception will increase the cost of concurrence so we increase the conflict value between them to 0.4.

		Task A				
		Visual	Auditory	Haptic	Working Memory	Manual
Task B	Visual	0.8	0.2	0.2	0.4	0.2
	Auditory		0.8	0.2	0.4	0.2
	Haptic			0.8	0.4	0.4
	Working Memory				0.8	0.2
	Manual					0.8

Table 4.1: Resource conflict matrix for two concurrent tasks in our study

Within this conflict matrix and demand vector for each task, the conflict level between two tasks can be calculated by using some specific method. In our method, we use the method described by Sarno and Wickens in the modified W/INDEX algorithm [122]. More details are presented in the subsequent section.

4.1.3.3 Calculate Potential Task Interference

For each task pair (in this study, one task is mobile HCI task and the other is contextual task in the scernario), the total potential interference consists of two components: demand and conflict component. The former penalizes the task pair for its total resource demand value and the latter penalizes a task pair according to the degree of conflict between tasks on resource pairs with a non-zero loading on both tasks [147].

In this study, the algorithm for calculating the total potential interference is based on the modified W/INDEX algorithm [122]. One main change is that we consider five cognitive resources in this study and only consider dual-task situations. In order to make it more intuitive and easy to use in computer, we translate it into pseudo code named as *Algorithm 1*, as shown in Figure 4.5.

Algorithm 1 Estimate Total Potential Interference in a Task-Scenario Pair

```
Require:
  The resource demand vector of the task, r_t[5];
  The resource demand vector of the scenarios, r_s[5];
  The conflict matrix, c_m[5, 5];
  The function for getting the sum of all elements in the array, sum(array name);
conflict = 0; totalInterference = 0;
for i = 0 to 4 do
  for j = i to 4 do
    if r_t[i] > 0 and r_s[j] > 0 then
      conflict = conflict + c_m[i, j] * (r_t[i] + r_s[j]);
    end if
  end for
end for
totalInterference = sum(r_t) + sum(r_s) + conflict;
return totalInterference;
```

Figure 4.5: Pseudo code for calculating total potential interference with conflict matrix

As mentioned before, we mainly consider the interference between mobile HCI tasks and mobile scenarios in this work. So this algorithm takes a resource vector of the mobile HCI task, a resource vector of the mobile scenario and a conflict matrix as inputs. For each value in the conflict matrix, if both corresponding resource demands are non-zero, then the production of the conflict value and the sum of the demands of those two resources is added to the conflict level for the task pair. The total potential interference is calculated by summing up the total resource demands of the task, the scenario and the conflict level.

4.1.3.4 Predict Mental Workload

After finishing above three steps, the interference value for each task pair can be gained. The interference value is not a direct measurement of mental workload in the real multitasking conditions because in our method users are not required to perform the specific mobile HCI task in the expected mobile scenario. Instead, the interference value is only a relative estimation for total potential interference between various task-scenario pairs. However, it does not prevent designers from predicting the trend of mental workload in different multitasking conditions.

For designers, by analyzing the trend of mental workload predicted by the total potential interference value in different multitasking conditions, it is easy to find the usability issues. Typically, compared to all predicted interference values, high values often suggest high mental workload. By further setting up certain threshold or baseline of acceptable interference level, designers can identify the usability problems according to resource competition resulting in the high interference. Not only the concrete interference values but also this prediction process itself can help designers to better understand and predict users' behavior.

4.2 Empirical Study

As mentioned earlier, it is very common for mobile HCI designers to deal with multitasking situations where the expected mobile interaction takes place in specific scenario. By taking those typical situations (task vs. scenario) into consideration, we conducted an empirical study with two phases – prediction and assessment – to verify our mental workload prediction method to see how well it can predict mental workload and investigate the mobile HCI in mobile scenarios as well. We designed six abstract HCI tasks to represent the typical operations in mobile interaction. Four typical mobile scenarios were selected.

4.2.1 Task Design

Inspired by the experiments in Coglab2 [41], six abstract tasks were designed. Here, “abstract” means that they were not real mobile HCI tasks but each of them represented one or more typical operations in mobile HCI.

4.2.1.1 Visual Search

A visual search task was designed by using the model of visual attention called the feature-integration theory of attention proposed by Treisman and Gelade [137]. In each trial of this task, several sticks with three properties – red and vertical, blue and vertical, red and horizontal – were presented to the participants, as shown in Figure 4.6. The participants were asked to determine whether there was a red and vertical stick by pressing one of the two volume buttons on the side of the mobile phone.

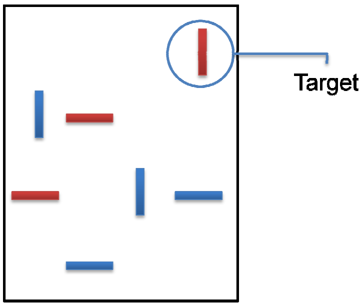

Figure 4.6: Illustration of visual search task (the target is the red and vertical stick)

4.2.1.2 Audio Comparison

In mobile interaction, auditory perception and related attention resources often play an important role as an alternative sensory for information retrieving. Therefore, we designed this task to observe human response performance relying solely on the auditory perception and attention. In this task, two sound clips sampled randomly from a pool of audio clips were played back in each trial and the participants had to determine whether the two sound clips were identical by pressing one of the two volume buttons on the side of the mobile phone.

4.2.1.3 Vibration Comparison

In addition to audio, vibration is also widely used in mobile interaction to provide tactile information. We investigated participants' haptic resources by asking them to compare vibration patterns in this task. The participants held a mobile phone on one hand where two vibration patterns – sampled randomly from a pool of five distinct vibration patterns as illustrated in Figure 4.7 – were displayed. As in the previous task, the participants had to choose whether two subsequent patterns were identical by selecting one of two volume buttons on the side of the mobile phone.

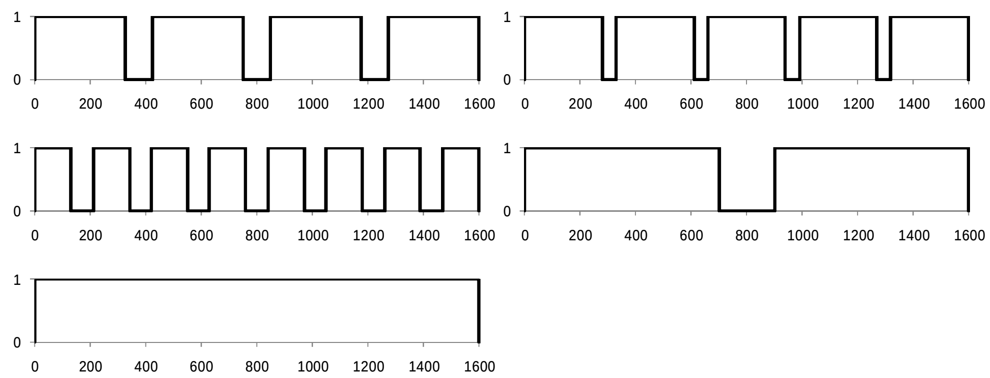

Figure 4.7: Five alternative vibration stimuli patterns examined in a task where users were asked to compare patterns. Each vibrating pattern lasted for 1.6 seconds. For each pattern, abscissa values are in milliseconds while ordinate values are either zero (idle mode) or one (active mode).

4.2.1.4 Memory Search

This task was designed based on the classic Sternberg Search [129] where in each trial a series of five numbers appeared on the screen of the mobile phone for 6 seconds. The participant needed to memorize the five numbers and used it as a basis of comparison against a new random number that appeared on the screen two seconds later. The participant had to determine whether the new random number was among the five numbers displayed earlier and pressed one of the two volume buttons on the side of the mobile phone.

4.2.1.5 Target Selection with Visual Target

The purpose of this task is to get an overview of participants' basic manual response with visual targets in different scenarios. In each trial, a red target was shown at a random position on the touch screen and the participant was asked to touch the target, as shown in Figure 4.8 (a).

4.2.1.6 Target Selection with Audio Target

On the touch screen phone, the screen is divided into grid of 4 rows by 3 columns where each tile is numbered sequentially based on its row and column position. The layout of the position of audio target is shown in Figure 4.8 (b). Each task began with the program saying a sequence of two numbers representing the target location in the grid. The participant would touch the screen to hear a sequence of two numbers representing the current position of the finger. The participant could then glide his/her finger to trigger audible feedback of the finger's position in the 4x3 grid. Upon finding the intended location, the participant could simply lift the finger off the screen to select it.

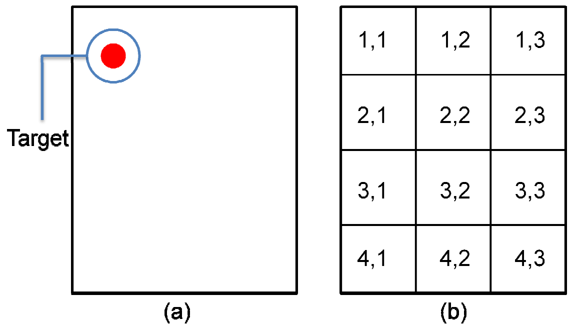

Figure 4.8: Illustration of two target selection tasks: (a) the illustration of the visual target; (b) the layout of the positions of audio target on the touch screen

4.2.2 Scenario Setting

Mobile devices are used in all aspects of life and mobile interaction can happen in any scenario. Investigating all of those possible scenarios is beyond the scope of our research and not very beneficial for mental workload prediction. In this study, we took the following four real-life situations – outdoor walking, lecture/meeting audience, public transportation and driving – into consideration, as shown in Table 4.2. The reason is that all of those four situations are very typical in mobile interaction. The influence on mobile interaction of those situations is not only from the requirement of mobility (e.g., outdoor walking) but also from the environmental and social parameters (e.g., lecture/meeting audience).

Based on these four real-life situations, we simplified each of them, as shown in Table 4.2. As mentioned, our focus was not to draw any rigorous theories. Thus we did not control everything in our designed scenarios. Instead, we provided a minimum representation of realistic scenarios. We asked participants to walk in campus to capture the influence of outdoor walking condition and asked them to take a shuttle bus to capture the influence while taking public transportation in real life. A driving simulator was used to simulate driving situation and we also organized several lectures to simulate the situation of being an audience in a lecture/meeting. Besides those four scenarios, a basic scenario was setup as the baseline, where participants completed all tasks in a quiet room without any interference.

Real-life Situations	**Set-up in this study**
Lecture/meeting audience	Simulated lecture
Outdoor walking	Walking in campus
Public transportation (e.g., bus)	Taking a shuttle bus
Driving (e.g., car)	Simulated driving

Table 4.2: The basic information of selected scenarios

4.2.2.1 Simulated Driving

The simulated driving scenario was conducted using a desktop driving simulator shown in Figure 4.9, coded in Java and OpenGL graphics library. Each participant was asked to drive a virtual car on the middle lane of a three-lane circuit while keeping a safe distance from nearby vehicles at the front and back of the participant's car. The leading car was moving at a constant speed of 105 km/h while the rear car – visible to the participant through the rear mirror – was following the participant's car at a distance (around 15m). Orange construction cones were placed along the lane dividers to encourage the participant to stay within the middle lane. The circuit was comprised of alternating straight and left curve segments at varying length which form a complete loop in counter-clockwise direction. An approximate 10-second interval was inserted between two trials in each round (The instructions were given by the experimenter) for each task to force participants focus on the driving task itself. After finishing all tasks, participants were required to drive for an additional 15 seconds before ending the session.

Figure 4.9: The illustration desktop of the driving simulator

4.2.2.2 Simulated Lecture

This simulated lecture was conducted in a meeting room in the campus. There was a table in the middle and 7 chairs around it. The participant was instructed to sit on a chair facing the projection screen where a 25-minutes video clip of "User Experience" obtained from the Internet was played in 1024×768 full screen mode. A notepad and stationery were provided to encourage note taking of key points in the given lecture. To facilitate note taking, ambient lighting was set at a comfortable level during the simulated lecture. The experimenter sent an oral reminder to the participants' mobile phone – signaling the beginning of the task – 3 minutes after the lecture video clip began.

4.2.2.3 Walking in Campus

This outdoor scenario was conducted in the campus. Participants were asked to walk at their own pace following a predefined counter-clockwise loop route passing through one canteen, two flights of stairs, and several aisles. The typical situation when participants performed this task was a number of tables and chairs along the walkway, lunch crowds, and ambient noise which usually peaks during lunch break. The participants were told to start walking from the same starting point and continue walking until all the tasks were completed.

4.2.2.4 Taking a Shuttle Bus

In this scenario, participants were asked to perform the given tasks on a shuttle bus. They always started the trips at the same bus stop. Participants were asked to remind the experimenter every time when the bus arrived at three specific bus stops. The purpose was to enhance the travelling experience. In this study, we did not limit their postures so all of them selected to sit.

4.2.3 Apparatus

One HTC Magic G2 with Android 1.5 was used as the mobile device with which the participants interacted. The phone is a touch screen phone and there are two volume buttons on the left side. The weight of the phone is 118.5g and the size of the phone is 113×55×13.65 mm so participants can hold it by using one hand. An earphone was used to help participants receive audio information. A video camera – Cannon H1 – was used to record participants' behavior in the study.

4.2.4 Procedure

The whole study had two steps: resource demand identification for prediction and empirical investigation for verification. In the first step, our mental workload prediction method was used based on the participants' self-reported data. In the second step, the empirical data was collected for further comparison with the predicted results.

4.2.4.1 Resource Demand Identification

First, participants were asked to perform each mobile HCI task with 10 trials. After finishing one task, participants had to identify the demand for each cognitive resource in this task by using a 6-scale questionnaire (0 for no demand, 5 for full demand). Then participants were asked to experience each scenario for a short time. After experiencing each scenario, participants also needed to identify the demand for each cognitive resource in each scenario. The whole procedure lasted about 45 minutes.

4.2.4.2 Empirical Investigation

Before starting the task, participants were briefed on the purpose of this study, got familiarized with the scenarios and informed that the entire study would be recorded. A

15-minute training was then conducted to get the participant to be familiarized with the experimental system and the task flow.

Each participant was individually presented with each of the five scenarios. In each scenario, each task contains four trials and after finishing one trial the next task started. So there were four rounds and in each round each task only presented one trial. Participants performed the tasks in the following order: *Visual Search*, *Audio Comparison*, *Vibration Comparison*, *Memory Search*, *Target Selection with Visual Target*, and *Target Selection with Audio Target*. The full-length study lasted for about four to five hours in total. Figure 4.10 illustrates the whole procedure. The Latin square used in this experiment is shown in the upper right corner of Figure 4.10. Participants were divided into five groups (1 – 5) and each group followed the corresponding sequence of scenarios indicated in the Latin square.

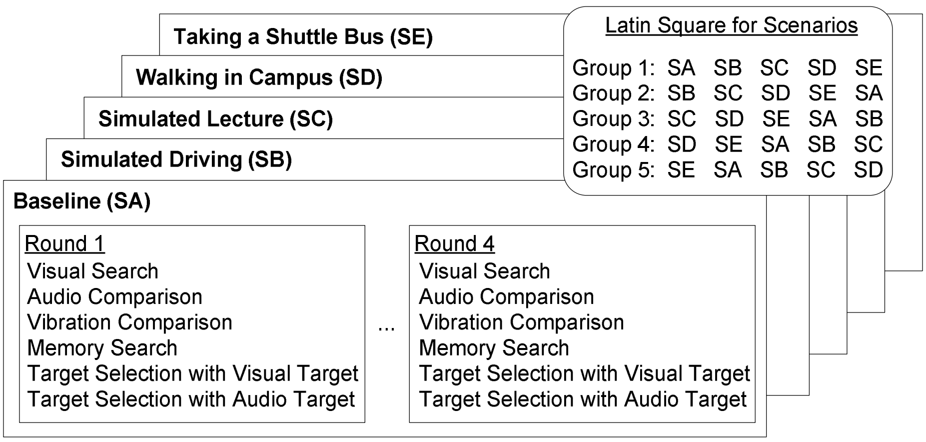

Figure 4.10: The procedure of empirical investigation (The Latin square is shown in the upper right corner)

To get a baseline, participants sat in a quiet room and completed all the tasks without any interference.

In the scenario *Simulated Driving*, participants were encouraged to familiarize themselves with the virtual environment as well as the controls—the steering wheel and acceleration pedals – by trying to drive the simulator for 20 minutes. They were then asked to drive the virtual car and maintain its course on the middle lane while keeping a safe distance of 15 meters from another car ahead. Once the safe distance was established, the participants might start the first task. The tasks were modified a little bit to adapt to the driving condition. An approximate 10-second interval was inserted between two tasks in each round (the instructions were given by the experimenter) for each task to force participants to focus on the driving task itself. After finishing all tasks, participants were required to drive for more 15 seconds before ending the session.

In the scenario *Simulated Lecture*, the experimenter sent an oral reminder to the participants – signaling the beginning of the task – 3 minutes after the lecture video clip began. All tasks were expected to be finished within 25 minutes. If the participants were unable to complete the given tasks, the video would continue until all tasks were finished. A short questionnaire was then given, covering the content of the lecture.

In the scenario *Walking in Campus*, participants started walking from the security post office of the selected building and were asked to start their tasks 10 seconds later as they were walking (the oral reminder was given by the experimenter). The route was a loop, so they could continue walking until all tasks had been completed.

In the scenario *Taking a Shuttle Bus*, participants were asked to be in a moving shuttle bus on weekdays to represent daily routines. After the bus left the bus stop, the participants were asked to start their tasks after an oral reminder was given by the experimenter. This session ended when all tasks were completed.

A NASA TLX Workload test was utilized at the end of each scenario to assess participants' mental workload while a more in-depth interview was conducted after the entire study was completed.

4.2.5 Participants

In resource demand identification, ten participants (male: 5, female: 5) from the university, aged from 21 to 25 (Mean: 23.2, SD: 1.14), were recruited to identify the resource demand of each task and scenario. All of them were right handed and they had been using mobile phones for 6.8 years in average (SD: 0.79)

In empirical investigation, another ten participants (male: 5, female: 5) from the university, aged from 21 to 27 (Mean: 23.8, SD: 1.81), took part in this empirical study. All of them were right handed and they had been using mobile phones for 7 years in average (SD: 0.82). A 5×5 Latin square shown in Figure 4.10 was used for counter balance on four scenarios and baseline.

We selected different groups of participants in order to better capture the predictive power because utilizing mental workload prediction often means that system evaluation is not conducted and participants just experience the prototype or use the system in high-simulation conditions, which is quite different from the system evaluation. In addition, recruiting same participants may lead to bias due to participants' preconceived feeling gained from the prediction phase.

4.2.6 Data Gathering

Data was gathered in the form of participants' rankings for resource demands of each task and scenario, mental workload and subjective comments. More specifically, these data were described as follows:

- Rankings for resource demands: a score (6-point scale was used in this paper) defined by the amount of use of each cognitive resource for one task/scenario.
- Mental workload: a score (11-point scale was used in this paper) defined by NASA TLX.
- Subjective comments: participants' subjective comments collected during the in-depth interview.

4.3 Results and Discussion

In this section, we first show the predicted results including resource demand vectors and total potential interference. We then present the empirical results measured by using NASA TLX, followed by a comparison between predicted interference and measured mental workload is presented. Lastly, we discuss the relationship between the response strategy and mental workload in this study.

4.3.1 Predicted Results

The raw data used in this section were collected in resource demand identification by asking participants to fill up 6-point scale questionnaires (0 for no demand, 5 for full demand). Then following our tailored prediction method, based on the calculated resource demand vectors of mobile HCI tasks and mobile scenarios, total potential interference value for each task-scenario pair was calculated.

4.3.1.1 Resource Demand Vectors for Mobile HCI Tasks and Mobile Scenarios

Based on participants' perceived demand scores (by getting the average values), resource demand vectors of the six mobile HCI tasks were calculated, as shown in Table 4.3. The demand scalar of each task was calculated by summing all resource demands in this task.

	Visual	Auditory	Haptic	Working Memory	Manual	Demand Scalar
Visual Search	4.2	0	0	0.5	0.2	4.9
Audio Comparison	0	4.8	0	2.3	0.3	7.4
Vibration Comparison	0	0.9	4.4	1.7	0.2	7.2
Memory Search	3.8	0	0	3.9	0.2	7.9
Target Selection with Visual Target	3.5	0	0	0	0.7	4.2
Target Selection with Audio Target	2.2	4.2	0	1.5	2.1	10.0

Table 4.3: Resource demand vectors of mobile HCI tasks (0 for no demand, 5 for full demand)

The results in Table 4.3 show that for participants each task had different focus on required cognitive resources, as we expected. For the task *Visual Search*, participants required a lot of visual resources (4.2) and did not need auditory and haptic resources. For the task *Audio Comparison*, auditory resources were required a lot (4.8) and participants did not need to use visual and haptic resources. As participants had to memorize the first audio clip, there was moderate requirement for working memory (2.3). For the task

Vibration Comparison, the main required cognitive resources were haptic resources (4.4). There was no requirement for visual resources. However, it is interesting to find that a little of auditory resources (0.9) were required in the task *Vibration Comparison*. As participants indicated, the sound caused by the vibration could be used to recognize the vibration. Also participants were required to memorize the first vibration pattern so there was a moderate requirement for working memory (1.7). For the task *Memory Search*, both visual resources (3.8) and working memory (3.9) were required a lot. Participants did not need auditory and haptic resources. For the task *Target Selection with Visual Target*, visual resources (3.5) were mainly required and participants did not need auditory and haptic resources as well as working memory. For the task *Target Selection with Audio Target*, auditory resources were required most (4.2). Although nothing was displayed in this task, in order to determine the position of the target, participants preferred to look at the screen and sometimes tried several times so there were a moderate requirement involved for visual resources (2.2) and a moderate requirement for manual resources involved (2.1).

The resource demand vectors of mobile scenarios are shown in Table 4.4 and the demand scalar of each scenario was calculated by summing all resource demands in each scenario.

	Visual	Auditory	Haptic	Working Memory	Manual	Demand Scalar
Simulated Driving	4.4	1.4	2.3	0.5	3.7	12.3
Simulated Lecture	3.9	4.6	0	1.8	2	12.3
Walking in Campus	2.2	1.3	1.1	0.2	2.2	7.0
Taking a Shuttle Bus	0.9	0.7	0.8	0.2	0.3	2.9

Table 4.4: Resource demand vectors of mobile scenarios (0 for no demand, 5 for full demand)

Compared to all the tasks, mobile scenarios required more diverse cognitive resources. All resources were required by the scenario ***Simulated Driving***, in which visual resources (4.4) and manual resources (3.7) were more desired for keeping their eyes on the road and controlling the wheel separately. The scenario ***Simulated Lecture*** mainly required visual resources (3.9) and auditory resources (4.6) so that participants could follow the lecture. In the scenario ***Walking in Campus***, the resource demands were moderate. Median demand levels of visual resources (2.2) and manual resources (2.2) were used to maintain walking behavior. In the scenario ***Taking a Shuttle Bus***, participants reported that all cognitive resources were required, but the demands were very low (< 1).

4.3.1.2 Total Potential Interference

After getting the resource demand vectors of all tasks and all scenarios, total potential interference for each task-scenario pair was calculated by using *Algorithm 1*. The results are shown in Table 4.5.

	Simulated Driving	Simulated Lecture	Walking in Campus	Taking a Shuttle Bus
Visual Search	34.72	33.18	25.24	17.64
Audio Comparison	36.54	37.20	28.76	21.84
Vibration Comparison	39.98	35.90	30.52	22.60
Memory Search	40.40	38.94	30.92	23.32
Target Selection with Visual Target	31.52	29.42	22.58	15.36
Target Selection with Audio Target	47.98	48.28	37.76	29.24

Table 4.5: Total potential interference between mobile HCI tasks and mobile scenarios by using *Algorithm 1*

The total potential interference values showed that for all tasks, the change of interference resulting from resource competition followed a certain trend. For the tasks required a lot of auditory resources, the maximum interference was caused by the concurrency with *Simulated Lecture*, while for other tasks the maximum interference was caused by the concurrency with *Simulated Driving*. For each task, *Taking a Shuttle Bus* always caused the minimum interference. The interference caused by concurrency with *Walking in Campus* was moderate.

4.3.2 Empirical Results

The overall mental workload measured by NASA TLX for each task in the four scenarios (*Simulated Driving, Simulated Lecture, Walking in Campus and Taking a Shuttle Bus*) is shown in Figure 4.11.

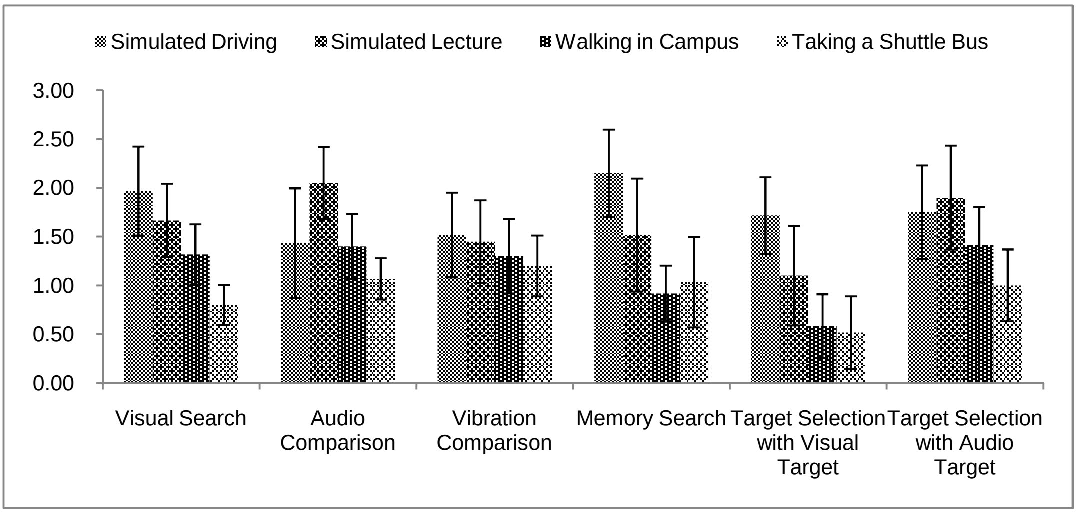

Figure 4.11: NASA TLX scores for different tasks in all scenarios

Among all tasks and scenarios, two-way repeated ANOVA analysis showed that there was a significant main effect of the type of tasks on participants' mental workload, $F(5, 45) = 8.83$, $p < .01$. Pairwise comparisons (Bonferroni) showed that the mental workload in

Target Selection with Visual Target (Mean = .98) was significantly lower than that in *Audio Comparison* (Mean = 1.49), *Memory Search* (Mean = 1.40) and *Target Selection with Audio Target* (Mean = 1.52), all $p < .05$.

There was also a significant main effect of the type of scenarios on participants' mental workload, $F(3, 27) = 41.95$, $p < .01$. Pairwise comparisons (Bonferroni) showed that participants had significantly lower mental workload in *Taking a Shuttle Bus* (Mean = .94) than *Simulated Driving* (Mean = 1.76), *Simulate Lecture* (Mean = 1.61) and *Walking in Campus* (Mean = 1.16), all $p < .05$. The mental workload in *Simulated Lecture* was significantly higher than that in *Walking in Campus*, $p < .05$. The mental workload in *Walking in Campus* was significantly lower than that in *Simulated Driving* and *Simulated Lecture*, all $p < .05$.

There was a significant interaction effect between the type of tasks and the type of scenarios used, $F(4.94, 44.44) = 5.55$, $p < .01$. This indicated that the scenario had different effects on participants' mental workload depending on which task was performed.

One-way repeated ANOVA was conducted on each task to capture the different influence of scenarios. For *Visual Search*, the results showed that participants' mental workload was significantly affected by the type of scenarios, $F(1.66, 14.91) = 22.72$, $p < .01$. Pairwise comparisons (Bonferroni) showed that participants had significantly lower mental workload in *Taking a Shuttle Bus* (Mean = .80) than that in *Simulated Driving* (Mean = 1.97), *Simulated Lecture* (Mean = 1.67) and *Walking in Campus* (Mean = 1.32), all $p < .01$. For *Audio Comparison*, the results also showed that participants' mental workload was significantly affected by the type of scenarios, $F(3, 27) = 10.62$, $p < .01$. Pairwise comparisons (Bonferroni) showed that mental workload in *Simulated Lecture* (Mean = 2.05) was significantly higher than that in *Walking in Campus* (Mean = 1.40) and *Taking a Shuttle Bus* (Mean = 1.07), all $p < .05$. For *Vibration Comparison*, mental workload had no significant difference in different scenarios, $F(1.84, 16.53) = 2.17$, $p > .05$. For *Memory Search*, the results showed that participants' mental workload was significantly affected by the type of scenario, $F(3, 27) = 19.82$, $p < .01$. Pairwise comparisons (Bonferroni) showed that participants' mental workload in *Simulated Driving* (Mean = 2.15) was significantly higher than that in *Walking in Campus* (Mean = .92) and *Taking a Shuttle Bus* (Mean = 1.03), all $p < .01$. Participants had significantly higher mental workload in *Simulated Lecture* (Mean = 1.52) than in *Walking in Campus* and *Taking a Shuttle Bus*, all $p < .05$. For *Target Selection with Visual Target*, participants had significantly different mental workload in difference scenarios, $F(3, 27) = 24.52$, $p < .01$. Pariwise comparisons (Bonferroni) showed that participants had significantly higher mental workload in *Simulated Driving* (Mean = 1.72) than in *Simulated Lecture* (Mean = 1.10), *Walking in Campus* (Mean = .58) and *Taking a Shuttle Bus* (Mean = .52), all $p < .05$. The results also showed that participants' mental workload in *Simulated Lecture* was significantly higher than that in *Taking a Shuttle Bus*, $p < .05$. For *Target Selection with Audio Target*, the results showed that participants' mental workload was significantly affected by the type of scenario, $F(3, 27) = 9.24$, $p < .01$. Pairwise comparisons (Bonferroni) showed that participants' mental workload in *Taking a Shuttle Bus* (Mean = 1.00) was significantly lower than that in *Simulated Driving* (Mean = 1.75) and *Simulated Lecture* (Mean = 1.90), all $p < .01$.

4.3.3 Comparison: Total Potential Interference vs. Measured Mental Workload

In this section, we compare the Total Potential interference and mental workload measured by NASA TLX to see how those two measurements correlated.

We further checked the normality of these two types of data. The one-sample Kolmogorov-Smirnov test showed that the distribution of total potential interference values ($p = .997$) and the distribution of NASA TLX scores ($p = .999$) were both normal distributions. Therefore, in the subsequent analysis, both Pearson and Spearman correlation are discussed to show the relationship between the total potential interference and NASA TLX scores.

Correlation	Negative	Positive
Zero	-.09 ~ 0	0 ~ .09
Weak	-.3 ~ .1	.1 ~ .3
Moderate	-.5 ~ -.3	.3 ~ .5
Strong	- 1 ~ -.5	.5 ~ 1

Table 4.6: The relationship between correlation and correlation coefficient

Many researchers have proposed different standards for interpreting correlations [26, 40]. For rigorous physical or chemistry experiments, the correlation of 0.9 may still be weak but the same value in social science could be very strong due to the existence of multiple factors. In this study, we adopted Cohen's proposal [26], which is shown in Table 4.6.

In order to get the overall effects of our tailored mental workload prediction method, we took each task-scenario pair as one data entry and then calculated the correlation between the interference values and NASA TLX scores for such pairs.

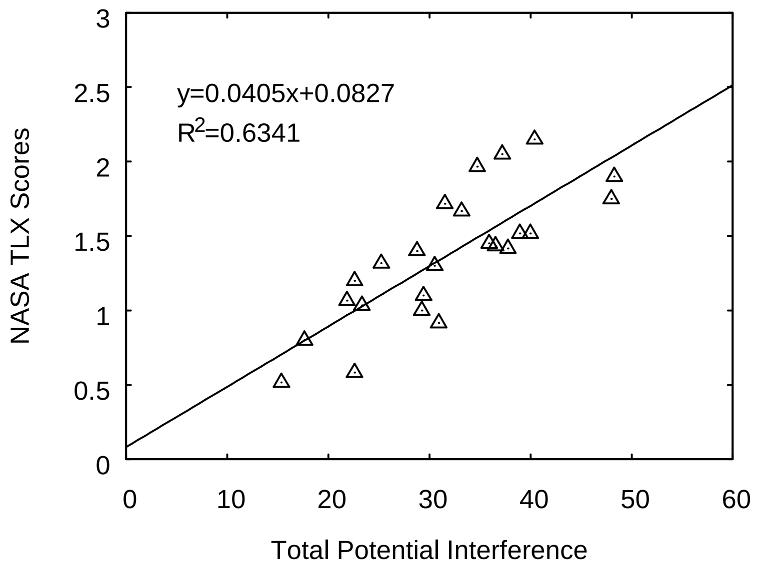

Figure 4.12: Scatter plot of NASA TLX Scores (Y-axis) on Total Potential Interference (X-axis)

Pearson correlation coefficient showed that there was a significantly high linear relationship between the interference values and corresponding NASA TLX scores, $r_p = .796$, $p < .01$. Spearman correlation coefficient showed that the NASA TLX scores were significantly correlated with the predicted interference values, $r_s = .835$, $p < .01$. Figure 4.12 plots the NASA TLX workload scores on the total potential interference values. A linear regression analysis was performed based on the simple assumption about the linear relationship between those two variables. The reported linear model can account for 63.41% of variation in NASA TLX scores. Nonetheless, we can confirm that the general trend of mental workload for different tasks in different scenarios can be predicted by total potential interference.

4.3.4 Response Strategy and Mental Workload

As previous research indicated, mental workload could be affected by response strategy [29]. According to the characteristics of dual-task settings in this study, there were three potential response strategies: task-first, scenario-first, and balanced. Task-first responders responded the mobile HCI task first while concurrent events came from both mobile HCI task and scenario. Scenario-first responders would like to deal with the event from the scenario first. Balanced responders tried to balance the performance in both mobile HCI task and corresponding scenario.

In this study, even for one participant, the response strategy was always changing and highly relied on the mobile scenario.

In the scenario *Walking in Campus*, all participants reported that they could handle the concurrent tasks (mobile HCI tasks vs. walking) and at most of time they were balanced responders. The similar situation happened in the scenario *Simulated Lecture*.

In the scenario *Taking a Shuttle Bus*, all participants selected task-first strategy because this scenario did not require too much participants' attention. As indicated by Table 4.5, this scenario produced the least mental workload. Therefore, participants could focus on mobile HCI tasks. One participant said, "*I didn't need to notice the bus too much, so I always focused on the (mobile HCI) tasks.*"

However, in the scenario *Simulated Driving*, driving required a lot of attention and all participants were asked to keep the car in the middle lane in a steady speed. For some participants, driving was not easy especially when visual attention was required simultaneously (e.g., doing visual search). Therefore they preferred dealing with the events related to driving first (scenario-first). As one participant indicated, "*I had to turn left at that time otherwise the car went out, even I knew the new (mobile HCI) task had started*." But for some participants who were relatively good at driving, they could well balance the concurrent tasks (balanced).

The response strategy affected mental workload by assigning priorities to the concurrent tasks while similar resources were shared. Task-first strategy assigned high priority to mobile HCI tasks so when different events for the task (e.g., reading the numbers) and scenario (e.g., walking) occurred, the shared resource (e.g., visual attention) was used to meet the mobile HCI task requirement first. Therefore, the perceived mobile HCI task difficulty was reduced and participants perceived low mental workload. In contrast, in scenario-first strategy resource was assigned to the scenario first so the perceived mobile HCI task difficulty was high and the mental workload increased. The influence of balanced strategy was more complex but overall this response strategy caused the relatively moderate mental workload. Although some work has been done (e.g., [30, 31]), in order to get in-depth understanding of the relationship between mental workload and response strategy more work is required, which is beyond the scope of our current focus and needs further investigation in the future.

4.4 Simplification for Mental Workload Prediction

Introducing users' self-reported data can reduce designers' workload and more importantly reduce the requirement of expertise. However, implementing a conflict matrix in step 2 still requires some expertise. Generally, designers need to implement such conflict matrix according to the real situations which they are facing by following the criterions we proposed. For example, when including the sense of smell [17] as input modality, the designers need to at least extend the conflict matrix we created or even establish a new one. To reduce the difficulty and inconvenience raised by implementing conflict matrix, we further simplify the step 2 by using the production of the requirements of shared resources to represent conflict level, as shown in Figure 4.13. Subsequently, more details about this simplification are presented.

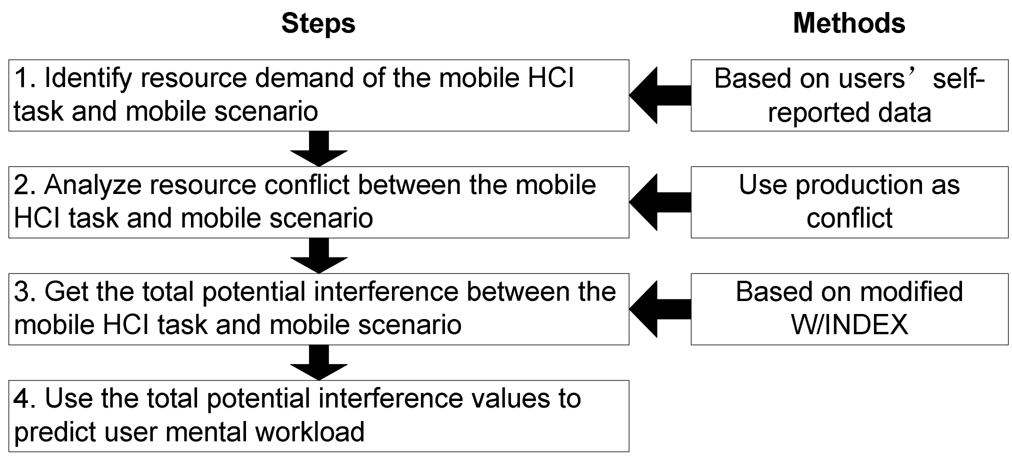

Figure 4.13: The process of the simplified version of mental workload prediction method

4.4.1 Deriving Interference from Resource Demand

The simplification is achieved by making two assumptions. First we assume that the conflict only occurs while the same cognitive resource is concurrently shared. Second, we assume that the conflict level is mainly determined by the resource demands in concurrent tasks. Therefore, we only focus on the shared resources and use the production of the demands of shared resources to represent conflict level. For example, if task A requires visual resource and auditory resource while the concurrent task B requires visual resource and haptic resource, the conflict level can be represented by the production of the visual resource demands in two tasks.

The algorithm shown in Figure 4.14, named as *Algorithm 2*, used to estimate total potential interference without using conflict matrix. After the resource demand vectors of one task and corresponding scenario are gained in step 1, the statements from line 1 to line 4 are used to calculate the conflict score between the task and the scenario. Then the total potential interference value is calculated by summing up the total resource demands of both the task and the scenario and the conflict score.

Algorithm 2 Estimate Total Potential Interference without Conflict Matrix

Require:

The set of resource demands of the task, $r_t[5]$;
The set of resource demands of the scenarios, $r_s[5]$;
The function for getting the sum of all elements in the array, *sum*(*array name*);

```
1: conflict = 0; totalInterference = 0;
2: for i = 0 to 4 do
3:   conflict = conflict + r_t[i] * r_s[i];
4: end for
5: totalInterference = sum(r_t) + sum(r_s) + conflict;
 return totalInterference;
```

Figure 4.14: Pseudo code for calculating total potential interference (without conflict matrix)

4.4.2 Predicted Results

Based on the resource demand vectors of mobile HCI tasks and mobile scenarios, total potential interference in each task-scenario pair was calculated by using *Algorithm 2*. The results are shown in Table 4.7.

	Simulated Driving	Simulated Lecture	Walking in campus	Taking a shuttle
Visual Search	36.67	34.88	21.68	11.74
Audio Comparison	28.68	46.52	21.76	14.21
Vibration Comparison	32.47	27.10	20.99	14.65
Memory Search	39.61	42.44	24.48	15.06
Target Selection with Visual Target	34.49	31.55	20.44	10.46
Target Selection with Audio Target	46.38	57.10	32.22	18.75

Table 4.7: Total potential interference between mobile HCI tasks and mobile scenarios by using *Algorithm 2*

Compared to the interference values in Table 4.5, ignoring the concrete values, the trend is almost same except that for the task *Memory Search* the maximum interference occurred in *Simulated Lecture* rather than *Simulated Driving*. The one-sample Kolmogorov-Smirnov test showed that the distribution of the interference values are normally distributed, $p = .845$.

4.4.3 Comparison: Total Potential Interference vs. Measured Mental Workload

We took each task-scenario pair as one data entry and then calculated the correlation between the interference values and NASA TLX scores for such pairs.

Pearson correlation coefficient showed that there was a significantly high linear correlation between the interference values and corresponding NASA TLX scores, $r_p = .823$, $p < .01$. Spearman correlation coefficient showed that the NASA TLX scores were significantly correlated with the interference values, $r_s = .895$, $p < .01$. Figure 4.15 plots the NASA TLX workload scores versus the interference values. Based on the simple assumption about the linear relationship between those two variables a linear regression analysis was performed. The reported linear model can account for 67.69% of variation in NASA TLX scores.

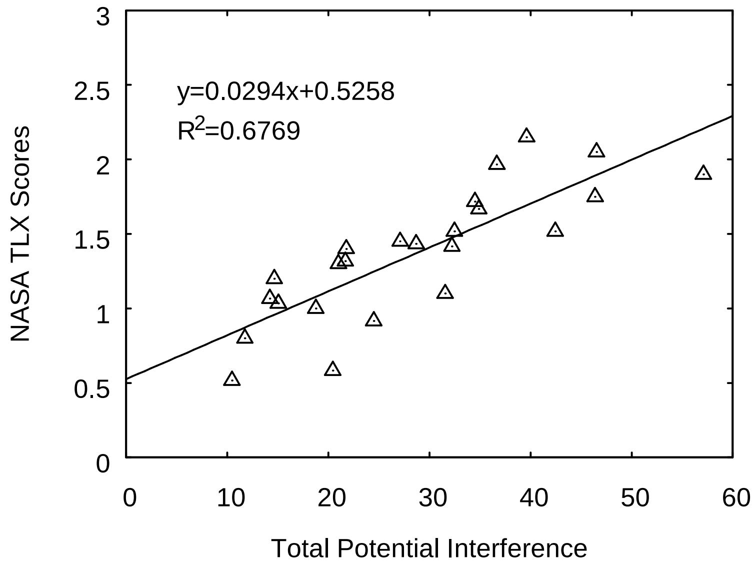

Figure 4.15: Scatter plot of NASA TLX Scores (Y-axis) on Total Potential Interference (X-axis)

4.5 Summary

The empirical study showed that our tailored mental workload prediction method and the simplified version both can correlate with the measured mental workload by using NASA TLX. The observation and participants' feedback showed that participants' response strategy can affect their mental workload but more investigation is required in the future.

Our attempt for adopting our tailored methods in predicting participants' mental workload also indicated some important issues to which should be paid attention by mobile HCI designers.

Firstly, the introduction of users' self-reported data can reduce the requirement of expertise and to a large extent to reflect users' real views. However, users' individual difference may affect their judgments. For example, a driver and a non-driver may give very different scores to driving simulation due to their different prior experience. Therefore, it is necessary to do some work to reduce the influence of individual difference before collecting users' self-reported data. There are some tips: 1) focus on the target users. If the mobile system is designed for children, it makes no sense to investigate it with elderly people; 2) if the target users are quite diverse, each time focus on one type of users; 3) in each round of prediction, make sure the users have homogenous background; 4) provide enough training/explanation even if only a paper prototype is shown to the users.

Secondly, the outcome of our mental workload prediction method is the relative level of interference rather than the absolute level of interference. Therefore, this method cannot help in the situation where there are only two concurrent tasks. By comparing the relative level of interference, designers can address the acceptable design (relatively low interference) and defective design (relatively high interference).

Thirdly, as we have emphasized, getting the predicted interference is not the only purpose. It is also important for designers to find the uncovered problems and collect users' feedback during the prediction procedure.

Fourthly, it is up to the designer to select either the method with or without conflict matrix as it depends on the expertise of the designers. If the method with conflict matrix is selected, it is important for designers to generate a proper conflict matrix according to the real situations. In contrast, if the simplified version is selected, the designer may face the fact that the predicted results may be rough.

Chapter 5

Conclusion

In this chapter, we first conclude our work in this thesis and then discuss the possible future directions related to our work.

5.1 Conclusions

We have presented our exploratory work on two usability factors in mobile HCI. This work consists of the exploration on user motivations for eyes-free interaction on mobile devices and the exploration on mental workload prediction in mobile HCI design.

We adopted a user-centered approach to explore motivations for eyes-free interaction on mobile devices via focus groups. Based on context dependency (contextual or independent) and realm (physical or human) we developed a four-category classification of motivations. We analyzed user motivations and sorted them into the four categories. We then discussed issues of diversity, concurrency and shifting of motivations, followed by design implications for eyes-free interactions in mobile device usage. Our work provides a different view of eyes-free interaction from the user’s perspective and helps to reveal insights and relationships among motivations. By enhancing the understanding of the motivations behind eyes-free interactions, we hope that better eyes-free interfaces can be created in the future.

We explored mental workload prediction for mobile HCI in different mobile scenarios. More specifically, we suggested a tailored mental workload prediction method by integrating multiple resource theory for resource analysis in mobile interaction, users' self-reported data for evaluating the resource demand, conflict matrix for identifying the resource conflict and modified W/INDEX for calculating dual-task interference. An empirical study with six tasks and four scenarios (plus one baseline) was conducted to evaluate our tailored mental workload prediction method, including two phases – prediction and assessment – with twenty participants involved totally. The high correlation between the predicted interference and measured mental workload indicated that the tailored mental workload prediction method can be used to predict the trend of mental workload in different dual-task conditions. However, implementing a conflict matrix still requires certain expertise, so we suggested using the production of the requirements of shared resources to represent conflict level. The analysis on empirical data using this simplified method also showed high correlation between predicted interference and measured mental workload. This work is the first attempt to explore mental workload prediction for mobile HCI in different mobile scenarios. For designers, they can simply extend our tailored method (with conflict matrix or without conflict matrix) to evaluate their designs for mobile interactive technologies in the early stage of the development process. For researchers, our work is a basis which can inspire them to investigate this topic more and possibly lead to better and easier mental workload prediction methods.

5.2 Future Directions

There are many open issues in our work that could be further explored.

For user motivations, more in-depth studies can be explored to provide more insights for designers. There are two possible directions.

Firstly, we explored user motivations by collecting participants' self-reported data in the focus groups. However, due to the limit of participants' memory, some interesting motivations may not be reported. In addition, how those reported motivations affect behavior is still not clear. Therefore, it is necessary to conduct long-term studies to investigate users' behavior/habits related to eyes-free interaction in their daily life.

Secondly, besides eyes-free interaction we mainly focused on in our current study, there are a lot of other novel mobile interaction techniques (e.g., hands-free). We believe that it is important to extend the research on user motivations in eyes-free interaction to other novel mobile interaction techniques. There could be at least two benefits: 1) derive design implications from user motivations for different mobile interaction techniques; 2) uncover the potential relationship between different mobile interaction techniques for design reuse.

For mental workload prediction, we did a very initial but first attempt to help designers predict users' mental workload in mobile HCI. Based on our current work, a lot of future directions can be explored.

Firstly, we only took a subjective measure – NASA TLX to measure participants' mental workload and compared it with the total potential interference. However, as Cain

[22] suggested, it could be better to conjunct NASA TLX with contextually relevant primary and embedded secondary task measures, which was not covered by this study because relatively real scenarios were selected where participants were not strictly limited to the dual-tasks and the task performance for different scenarios are not easy to compare. In the future, stricter dual-task situations could be conducted to embed primary and secondary task measures so that we can further compare interference with measured mental workload from various aspects.

Secondly, we noticed that response strategy could affect mental workload. Taking the characteristics of mobile interaction (e.g., mobility and multitasking) into account, how response strategy affects mental workload is still largely unclear. In order to illuminate the relationship between response strategy and mental workload in mobile interaction, the following work can be done in the future: 1) get a systematic taxonomy of users' response strategies in mobile interaction; 2) conduct several studies to compare the influence of different response strategies on mental workload in specific mobile scenarios; 3) according to the results, try to find common patterns.

Thirdly, our results already showed the feasibility of mental workload prediction for mobile HCI in different scenarios. However, there is still a lack of investigation about its usage in the real development of mobile system. Therefore, we hope to conduct a study of mental workload prediction in real mobile system development. By doing that, we want to explore how the suggested methods (original and simplified versions) can guide designers to better design and address the potential problems when using these methods. This would provide more real data for us to gain more insights.

Fourthly, we have found that users could be motivated to choose mobile interaction technique by the motivation of lowering the perceived mental workload, but how motivations affect mental workload in mobile HCI is still unclear. In the future, more studies can be done to further uncover the relationship between motivations and mental workload in mobile HCI.

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Appendix A

Consent Forms

A.1 Participant Information Sheet & Consent Form (User Motivation – Focus Group)

"Exploring User Motivations for Eyes-free Interaction on Mobile Devices"

Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Juliana Ung
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

You are invited to participate in a research study titled "Exploring User Motivations for Eyes-free Interaction on Mobile Devices". This information sheet provides you with information about the research. The investigator (the research doctor or person in charge of this research) or his representative will also describe this research to you and answer all of your questions. Please read the information below and ask questions about anything you don't understand before deciding whether or not to take part.

Purpose of Research: This research examines user motivations in choosing eyes-free technologies for mobile interaction. The ultimate goal of this research is to provide a classification of motivations for eyes-free interaction to help designers.

Number of Participants and Inclusion Criteria: About 20 English-speaking participants will be recruited for several focus groups. You should have rich experience on mobile devices usage.

What Will You Be Asked to Do and Where: You are invited to participate in 1 focus group that lasts 1 to 2 hours. During the focus group, you will be asked to discuss the topics given by the investigator with other participants. The focus groups will be conducted in Meeting Room 6 in School of Computing, NUS.

Confidentiality and Publication of Results: Personal information collected will include your name and contact information, which will be coded (i.e., identified with a code number) to protect your confidentiality. You age, gender, employment status, education level and experience on mobile devices use will also be collected. Your name will **not** be published and the other information collected will be aggregated together as a percentage or classified as a group. Your personal information will not be revealed in any publication related to this research.

Use of the Video-Recording and Audio-Recording: The focus group will be both filmed and audio-recorded. The video and audio materials will only be studied by the research team for use in this research project. All of those data will be put in an internal secure sever. For other release issues, we would like your permission to use these materials in academic conferences, academic discussions, educational settings, and public presentations.

Notification: Although your name will never be revealed, it may be possible for someone who knows you to recognize your voice from the audio materials.

Risks and Benefits: There is no direct benefit to you from participating in this focus group and the researchers do not foresee any risks from your participation. You are free to decline to answer any question that you feel uncomfortable with or to stop participating in the focus group whenever you wish.

Can I refuse to participate in this research? Yes, you can. Your decision to participate in this research is voluntary and completely up to you. You can also withdraw from the research at any time without giving any reasons, by informing the investigator and all your data collected will be discarded.

Reimbursement: You will be reimbursed **S$15** for participating in the research. You will be reimbursed for the time you participated in the research, regardless of whether you are able to finish the focus group.

Access to Information: The research team, Shengdong Zhao and his colleagues and students, will have access to the data in its raw and coded forms. Records of the focus group will be kept for the period of approximately 10 years. All retained information will be coded.

Contact Information:
Please contact Bo Yi for further information.
Phone: 65-6516-4361 Email: nushcilab@gmail.com

Consent Form

Project title: Exploring User Motivations for Eyes-free Interaction on Mobile Devices
Principal Investigator and co-investigators with the contact number and organization:
Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Juliana Ung
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

I hereby acknowledge that:

I have read the information provided to me on this focus group and I hereby consent to participate in the study "Exploring User Motivations for Eyes-free Interaction on Mobile Devices". The objectives, methods, and procedures have been thoroughly explained to me and all of my questions and concerns of the focus group have been answered completely to my satisfaction.

I have the right to withdraw from this focus group at any point in the focus group without penalty, and to request that my data be destroyed. If I decide to withdraw from the experiment before finishing, I will be reimbursed according to the time I spent on the experiment at the rate of S$15/hour.

I give* permission for the research team to use the above video and audio materials in the following way:
It can be submitted to scientific conferences.
Video: ☐ Yes ☐ No Audio: ☐ Yes ☐ No
It can be shown at meetings of scientists interested in the study.
Video: ☐ Yes ☐ No Audio: ☐ Yes ☐ No
It can be shown in classrooms to students.
Video: ☐ Yes ☐ No Audio: ☐ Yes ☐ No
It can be show in public presentations to nonscientific groups.
Video: ☐ Yes ☐ No Audio: ☐ Yes ☐ No
It can be used on television and radio.
Video: ☐ Yes ☐ No Audio: ☐ Yes ☐ No
*please indicate

I understand that my name will not be published in connection with any such presentation or publication. I will not receive any compensation for the use of the recordings or photographs. I will receive a copy of this consent form.

______________________________ __________

Name and Signature (Participant) Date

Name and Signature (Consent Taker) Date

A.2 Participant Information Sheet & Consent Form (Mental Workload Prediction – Experiment for Resource Demand Identification)

“Exploring Mental Workload Prediction in Mobile HCI Design”

Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Chris Prasojo
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

You are invited to participate in a research study titled “Exploring Mental Workload Prediction in Mobile HCI Design”. This information sheet provides you with information about the research. The investigator (the research doctor or person in charge of this research) or his representative will also describe this research to you and answer all of your questions. Please read the information below and ask questions about anything you don’t understand before deciding whether or not to take part.

Purpose of Research: This research examines users’ mental workload while performing mobile HCI tasks in mobile scenarios. The ultimate goal of this research is to provide a mental workload predication method for mobile HCI designers.

Number of Participants and Inclusion Criteria: About 10 English-speaking participants will be recruited for this experiment. You should have rich experience on mobile devices usage without any physical disability.

What Will You Be Asked to Do and Where: You are invited to participate in one experiment that lasts around 45 minutes. During the experiment, you will be asked to complete 6 mobile HCI tasks and experience 4 scenarios guided by the experimenter. After completing 1 task or experiencing 1 scenario, you will be asked to fill a simple questionnaire. The experiment will be conducted in meeting room in School of Computing, NUS, the campus of NUS and the shuttle bus of NUS.

Confidentiality and Publication of Results: Personal information collected will include your name and contact information, which will be coded (i.e., identified with a code number) to protect your confidentiality. You age, gender, employment status, education level and experience on mobile devices use will also be collected. Your name will **not** be published and the other information collected will be aggregated together as a percentage or classified as a group. Your personal information will not be revealed in any publication related to this research.

Risks and Benefits: There is no direct benefit to you from participating in this experiment and the researchers do not foresee any risks from your participation. You are free to decline to answer any question that you feel uncomfortable with or to stop participating in the experiment whenever you wish.

Can I refuse to participate in this research? Yes, you can. Your decision to participate in this research is voluntary and completely up to you. You can also withdraw from the research at any time without giving any reasons, by informing the investigator and all your data collected will be discarded.

Reimbursement: You will be reimbursed **S$10** for participating in the research. You will not be reimbursed if you cannot finish the experiment.

Access to Information: The research team, Shengdong Zhao and his colleagues and students, will have access to the data in its raw and coded forms. Data of the experiment will be kept for the period of approximately 10 years. All retained information will be coded.

Contact Information:
Please contact Bo Yi for further information.
Phone: 65-6516-4361 Email: nushcilab@gmail.com

Consent Form

Project title: Exploring Mental Workload Prediction in Mobile HCI Design
Principal Investigator and co-investigators with the contact number and organization:
Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Chris Prasojo
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

I hereby acknowledge that:

I have read the information provided to me on this experiment and I hereby consent to participate in the study “Exploring Mental Workload Prediction in Mobile HCI Design”. The objectives, methods, and procedures have been thoroughly explained to me and all of my questions and concerns of the experiment have been answered completely to my satisfaction.

I have the right to withdraw from this experiment at any point in the experiment without penalty, and to request that my data be destroyed. If I decide to withdraw from the experiment before finishing, I will not be reimbursed.

I understand that my name will not be published in connection with any such presentation or publication. I will not receive any compensation for the use of the recordings or photographs. I will receive a copy of this consent form.

______________________________ __________

Name and Signature (Participant) Date

______________________________ __________

Name and Signature (Consent Taker) Date

A.3 Participant Information Sheet & Consent Form (Mental Workload Prediction – Experiment for Empirical Investigation)

"Exploring Mental Workload Prediction in Mobile HCI Design"

Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Chris Prasojo
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

You are invited to participate in a research study titled "Exploring Mental Workload Prediction in Mobile HCI Design". This information sheet provides you with information about the research. The investigator (the research doctor or person in charge of this research) or his representative will also describe this research to you and answer all of your questions. Please read the information below and ask questions about anything you don't understand before deciding whether or not to take part.

Purpose of Research: This research examines users' mental workload while performing mobile HCI tasks in mobile scenarios. The ultimate goal of this research is to provide a mental workload predication method for mobile HCI designers.

Number of Participants and Inclusion Criteria: About 10 English-speaking participants will be recruited for this experiment. You should have rich experience on mobile devices usage without any physical disability.

What Will You Be Asked to Do and Where: You are invited to participate in one experiment that lasts 4 – 5 hours. During the experiment, you will be asked to complete 6 mobile HCI tasks in 5 scenarios guided by the experimenter. After completing all tasks in 1 scenario, you will be asked to fill a simple questionnaire. In the end of the experiment, you will be asked to attend a short interview. The experiment will be conducted in meeting room in School of Computing, NUS, the campus of NUS and the shuttle bus of NUS.

Confidentiality and Publication of Results: Personal information collected will include your name and contact information, which will be coded (i.e., identified with a code number) to protect your confidentiality. You age, gender, employment status, education level and experience on mobile devices use will also be collected. Your name will **not** be published and the other information collected will be aggregated together as a percentage or classified as a group. Your personal information will not be revealed in any publication related to this research.

Use of the Video-Recording: The experiment will be video-recorded. The video materials will only be studied by the research team for use in this research project. All of those data will be put in an internal secure sever. For other release issues, we would like your permission to use these materials in academic conferences, academic discussions, educational settings, and public presentations.

Risks and Benefits: There is no direct benefit to you from participating in this experiment and the researchers do not foresee any risks from your participation. You are free to decline to answer any question that you feel uncomfortable with or to stop participating in the experiment whenever you wish.

Can I refuse to participate in this research? Yes, you can. Your decision to participate in this research is voluntary and completely up to you. You can also withdraw from the research at any time without giving any reasons, by informing the investigator and all your data collected will be discarded.

Reimbursement: You will be reimbursed **S$25** for participating in the research. You will not be reimbursed if you cannot finish the experiment.

Access to Information: The research team, Shengdong Zhao and his colleagues and students, will have access to the data in its raw and coded forms. Data of the experiment will be kept for the period of approximately 10 years. All retained information will be coded.

Contact Information:
Please contact Bo Yi for further information.
Phone: 65-6516-4361 Email: nushcilab@gmail.com

Consent Form

Project title: Exploring Mental Workload Prediction in Mobile HCI Design
Principal Investigator and co-investigators with the contact number and organization:
Investigator: Bo Yi
Co-investigators: Shengdong Zhao and Chris Prasojo
Department of Computer Science, National University of Singapore
Computing 1, 13 Computing Drive, Singapore 117590. Phone: 65-6516-4361

I hereby acknowledge that:

I have read the information provided to me on this experiment and I hereby consent to participate in the study “Exploring Mental Workload Prediction in Mobile HCI Design”. The objectives, methods, and procedures have been thoroughly explained to me and all of my questions and concerns of the experiment have been answered completely to my satisfaction.

I have the right to withdraw from this experiment at any point in the experiment without penalty, and to request that my data be destroyed. If I decide to withdraw from the experiment before finishing, I will not be reimbursed.

I give* permission for the research team to use the above video materials in the following way:
The video can be submitted to scientific conferences.
☐ Yes ☐ No
The video can be shown at meetings of scientists interested in the study.
☐ Yes ☐ No
The video can be shown in classrooms to students.
☐ Yes ☐ No
The video can be show in public presentations to nonscientific groups.
☐ Yes ☐ No
The video can be used on television and radio.
☐ Yes ☐ No
*please indicate

I understand that my name will not be published in connection with any such presentation or publication. I will not receive any compensation for the use of the recordings or photographs. I will receive a copy of this consent form.

______________________________ ____________

Name and Signature (Participant) Date

______________________________ ____________

Name and Signature (Consent Taker) Date

Appendix B

Questionnaires

B.1 Pre-experiment Questionnaire

1. What is your age?

____

2. What is your gender?

☐ Male ☐ Female

3. What is your current employment status?

☐ Student ☐ Employed ☐ Unemployed ☐ Self-employed

If you choose "Student", please indicate your major here ________________

If you choose "Employed", please indicate your occupation here ______________

If you choose "Self-employed", please indicate industry here ________________

4. What is your education level?

☐ High school ☐ Bachelor ☐ Master ☐ PhD ☐ Others

5. What is the brand of your mobile phone?

____

6. How many years have you used mobile phones?

☐ <=1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ >8

7. Are you a left-handed or right-handed person while using the mobile phone?

☐ Left-handed ☐ Right-handed ☐ Other

8. What's the type of your mobile phone?

☐ Keypad ☐ Touch Screen ☐ Stylus ☐ Others __________

9. What are the applications in you mobile phone do you often use?

____

10. Besides mobile phone, what kinds of other mobile devices do you often use?

____

B.2 Questionnaire for Identifying Resource Demand for Task

Task Name ___________________ Participant ID_____________________

1. How much visual attention did you pay to the task?
(Does the task require you to look at something? If so, how much do you need to concentrate on it? 0: I don’t need to pay visual attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the task.)

(no demand) 0 1 2 3 4 5 (full demand)

2. How much auditory attention did you pay to the task?
(Does the task require you to listen to something? If so, how much do you need to concentrate on it? 0: I don’t need to pay auditory attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the task.)

(no demand) 0 1 2 3 4 5 (full demand)

3. How much haptic attention did you pay to the task?
(Does the task require you to feel the stimuli by touch or force? If so, how much do you need to concentrate on it? 0: I don’t need to pay haptic attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the task.)

(no demand) 0 1 2 3 4 5 (full demand)

4. How much motor control did you use in this task?
(Do you need to control you hand or leg in the task? If so, how much do you need to concentrate on it? 0: I don’t need to pay attention to control my hands or my legs. 5: I can’t switch my attention at all and I need to pay full attention to the control.)

(no demand) 0 1 2 3 4 5 (full demand)

5. How much working memory did you use in this task?
(Do you need to memorize some information in this task? If so, how much do you need to memorize? 0: I don’t need to memorize anything. 5: I have to pay full attention to memorizing.)

(no demand) 0 1 2 3 4 5 (full demand)

B.3 Questionnaire for Identifying Resource Demand for Scenario

Scenario Name ________________ Participant ID__________________

1. How much visual attention did you pay to the scenario?
(Does the scenario require you to look at something? If so, how much do you need to concentrate on it? 0: I don’t need to pay visual attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the scenario.)

(no demand) 0 1 2 3 4 5 (full demand)

2. How much auditory attention did you pay to the scenario?
(Does the scenario require you to listen to something? If so, how much do you need to concentrate on it? 0: I don’t need to pay auditory attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the scenario.)

(no demand) 0 1 2 3 4 5 (full demand)

3. How much haptic attention did you pay to the scenario?
(Does the scenario require you to feel the stimuli by touch or force? If so, how much do you need to concentrate on it? 0: I don’t need to pay haptic attention to it at all. 5: I can’t switch my attention at all and I need to pay full attention to the scenario.)

(no demand) 0 1 2 3 4 5 (full demand)

4. How much motor control did you use in this scenario?
(Do you need to control you hand or leg in the scenario? If so, how much do you need to concentrate on it? 0: I don’t need to pay attention to control my hands or my legs. 5: I can’t switch my attention at all and I need to pay full attention to the control.)

(no demand) 0 1 2 3 4 5 (full demand)

5. How much working memory did you use in this scenario?
(Do you need to memorize some information in this scenario? If so, how much do you need to memorize? 0: I don’t need to memorize anything. 5: I have to pay full attention to memorizing.)

(no demand) 0 1 2 3 4 5 (full demand)

B.4 NASA Task Load Index

Participant ID ___________ Task ___________ Scenario ___________

Mental Demand
(How mentally demanding was the task?)
(Very Low) 0 1 2 3 4 5 6 7 8 9 10 (Very High)

Physical Demand
(How physically demanding was the task?)
(Very Low) 0 1 2 3 4 5 6 7 8 9 10 (Very High)

Temporal Demand
(How hurried or rushed was the pace of the task?)
(Very Low) 0 1 2 3 4 5 6 7 8 9 10 (Very High)

Performance
(How successful were you in accomplishing what you were asked to do?)
(Good) 0 1 2 3 4 5 6 7 8 9 10 (Poor)

Effort
(How hard did you have to work to accomplish your level of performance?)
(Very Low) 0 1 2 3 4 5 6 7 8 9 10 (Very High)

Frustration
(How insecure, discouraged, irritated, stressed, and annoyed were you?)
(Very Low) 0 1 2 3 4 5 6 7 8 9 10 (Very High)

B.5 Post-experiment Open-ended Interview Questions

Participant ID __________________ Date __________________

In *Simulated Driving* scenario

1. Did you have difficulties/troubles in finishing the tasks?

☐ Yes ☐ No

If "Yes", please describe:

(a) What were the difficulties/troubles?

____

(b) Which tasks were related to those difficulties/troubles?

____

(c) How did you solve them?

____

If "No", please indicate:

(a) Why did you think there was no any difficulty/trouble?

____

2. Which similar experience did you have in your daily life?

____

In *Simulated Lecture* scenario

1. Did you have difficulties/troubles in finishing the tasks?

☐ Yes ☐ No

If "Yes", please describe:

(a) What were the difficulties/troubles?

____

(b) Which tasks were related to those difficulties/troubles?

____

(c) How did you solve them?

____

If "No", please indicate:

(a) Why did you think there was no any difficulty/trouble?

____

2. Which similar experience did you have in your daily life?

____

In *Walking in Campus* scenario

1. Did you have difficulties/troubles in finishing the tasks?

☐ Yes ☐ No

If "Yes", please describe:

(a) What were the difficulties/troubles?

____

(b) Which tasks were related to those difficulties/troubles?

(c) How did you solve them?

If “No”, please indicate:

(a) Why did you think there was no any difficulty/trouble?

---

2. Which similar experience did you have in your daily life?

In *Taking a Shuttle Bus* scenario

1. Did you have difficulties/troubles in finishing the tasks?

☐ Yes ☐ No

If “Yes”, please describe:

(a) What were the difficulties/troubles?

(b) Which tasks were related to those difficulties/troubles?

(c) How did you solve them?

If “No”, please indicate:

(a) Why did you think there was no any difficulty/trouble?

---

2. Which similar experience did you have in your daily life?
