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NURSING INTERRUPTION DYNAMICS: THE IMPACT OF WORK SYSTEM FACTORS

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ABSTRACT

Interruptions occur frequently in healthcare work systems. Hands-free Communication Devices (HCDs) were implemented in healthcare work systems to support the interruption process. However, from a sociotechnical systems perspective, HCDs may introduce new complications and unintended consequences to the work system. Research gaps exist in investigating the complexity of HCD interruptions in the real-world context. This dissertation aims to understand HCD interruption dynamics in the nursing work systems, using qualitative research methods. The first study examined the major differences between face-to-face and HCD-mediated interruptions, based on 30 hours of field observations in the acute care setting. Three major differences included: (1) The available cues to understand interruptee's interruptibility, (2) The delivery of interruption content, and (3) The options to manage interruptions. The results uncovered facilitators and barriers that appeared to influence nursing work in the interruption process. The second study explored HCD interruption dynamics in more depth. It examined which system factors impact the interruption dynamics and how they influence nurses' decisions and performance regarding the use of HCDs, based on 15 hours of field observations and 15 in-depth interviews with registered nurses in the pediatric intensive care units. This study was framed by the meso-ergonomics paradigm and activity theory. A descriptive model of HCD interruption dynamics was developed, comprising of five proximal system factors, 17 indicator and moderator system factors, and four distal system factors. These system factors interact and create integrated causal chains to impact interruption dynamics and influence the nurses' decisions and performance

regarding the use of HCDs. Specifically, the proximal system factors immediately impact interruption dynamics, the indicator or moderator system factors provide partial inputs and contextual circumstances of the proximal system factors, and the distal system factors are further down the causal chain. The results of the dissertation provided the basis for improving the design of interruption-mediating tools as well as the nursing work system, to better support the HCD-mediated interruption process, which may ultimately enhance the quality and safety of healthcare work systems.

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CHAPTER 1: OVERVIEW

The healthcare system is a complex sociotechnical system, with heterogeneous characteristics, dynamic disturbances, uncertainty, large problem spaces, hazardous errors, and ubiquitous technology (Carayon et al., 2006). Healthcare Professionals (HCPs), especially nurses, need to stay informed with real-time updates regarding their patients for task planning and problem-solving (Manser, 2009). Similar to the domains of aviation and transportation, interruptions are common occurrence in the healthcare system, and have been associated with medication errors (Institute of Medicine, 2000; Flynn et al., 1999; Wiegmann, ElBardissi, Dearani, Daly, & Sundt, 2007). Although limited evidence has validated a direct causal relationship between interruptions and medical errors (Grundgeiger & Sanderson, 2009), from a systems perspective and using the "Swiss Cheese" model, interruptions can be deemed as latent contributors bearing the potential to have detrimental effects to patient safety (Reasons, 1990; Biron, Lavoie-Tremblay, & Loiselle, 2009). Motivated by their potential risks, the research of interruptions in healthcare has become prevalent in recent years. Studies have been conducted to understand the frequency and impact of interruptions (Drews, 2007), to determine the proximal sources of interruptions (Hedberg & Larsson, 2004), and to validate the linkage between interruptions and medication administration errors (Westbrook, Woods, Rob, Dunsmuir, & Day, 2010).

Interruptions can be initiated by a person, such as physicians, nurses, residents, pharmacist, nurse assistants, nurse students, patients, or patient's family members (Laxmisan et al., 2007; Friedman, Elinson, & Arenovich, 2005; Peleg, et al., 2000).

Interruptions can also be initiated by a technology, such as an alarm, alert, or beeping from the patient monitor (vitals or otherwise), the electronic health record system, and barcode medication administration system (Hedberg & Larsson, 2004). Interruptions can also be caused by environmental factors, known as operation failures, which hinder the current workflow and ability to provide information, services, materials, and supplies when they are needed (Tucker & Spear, 2006). Based on the existing research, the most frequent source of interruption in healthcare are nurses (Biron et al., 2009), and the most preferred method is through face-to-face communication (Alverez & Coiera, 2005).

With the implementation of communication devices in healthcare systems, the channels of interruptions have been enriched, the pathways including, but not limited to, telephones, paging systems, mobile phones, and task management systems (Wu et al., 2012). Hands-free Communication Devices (HCDs) are also mediating tools for interruptions (Breslin, Greskovich, & Turisco, 2004; de Grood et al., 2012; Jacques, France, Pilla, Lai, & Higgins, 2006). If integrated well into the work system, HCDs can help nurses recover from detrimental effects of interruptions (Andrews, Ratwani, & Trafton, 2009). Otherwise, they may introduce new complications and unintended consequences to the work system. In either case, we still lack an understanding of HCD-mediated interruptions and their influences on performance and decisions from a systems perspective.

Interruptions are situated in the context of the healthcare work system (Brixey et al., 2007; Magrabi, Li, Dunn, & Coeira, 2011), increasing their complexity and requiring deeper insights (Rivera-Rodriguez & Karsh, 2010). The aims of this dissertation are to

understand the HCD-mediated interruption dynamics in the real-world context and their influences on nurses' decisions and performance when using such devices. The specific aims are:

- Aim 1: To understand HCD interruption dynamics in a nursing work system. This aim was achieved by field observations in the acute care setting.
- Aim 2: To understand the impact of system factors on HCD interruption dynamics and the influences of system factors on nurses' decisions and performance regarding the use of HCDs. This aim was achieved by field observations and interviews in the pediatric intensive care setting.

This dissertation document includes five chapters. Chapter 2 is a literature review that will be submitted to BMJ Quality and Safety. This paper reviews the previous reviews and summaries of the interruption research in healthcare, and identifies the remaining research gaps that still exist as identified in previous reviews. Chapter 3 is a research paper published in 2015 in Health Policy and Technology. This paper examines how the integration HCDs differentiates the interruption dynamics from the existing knowledge of face-to-face interruptions in a nursing work system (Aim 1). Chapter 4 is a paper that will be submitted to Applied Ergonomics. This paper presents a qualitative research study to understand the impact of system factors on HCD interruption dynamics and their influences on nurses' decisions and performance regarding the use of HCDs (Aim 2). Chapter 5 concludes by presenting the contribution of this dissertation and future research directions.

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CHAPTER 2: LITERATURE REVIEW

Research on interruptions in healthcare has flourished in recent years. Research questions have been varied, ranging from "What is an interruption?" (Drews, 2007), to "How can we classify interruptions based on various characteristics, such as their source, content, channel, and psychological impacts?" (Fargen, O'Connor, Raymond, Sporrer, & Friedman, 2012), and to "What are the best strategies to manage interruptions?" (Colligan & Bass, 2012). Reviews of the interruption research have been conducted, which have enhanced our understanding of interruptions and have motivated researchers to expand their ways of thinking about the problem. This chapter consists of a literature review of the systematic reviews and summaries of research on interruptions in healthcare. The objectives of this chapter are to summarize the research gaps identified by the previous reviews, and examine which research gaps identified in those review papers that have and have not been addressed. A literature review of systematic reviews and summaries is unique, but significant for the following reasons: (1) Since most of the interruption studies have been reviewed by previous researchers, conducting yet another literature review in the same way will not advance our knowledge of the topic; (2) The findings in the systematic reviews and summaries have not yet been synthesized, so an aggregate compilation of past reviews can provide a complete picture, showing the progression of interruption research in healthcare; (3) Demonstrating the progression of interruption research will provide insight on previously identified gaps that have been addressed, gaps that currently exist, and prospective research. Therefore, by bridging together all the systematic reviews and summaries of interruptions in healthcare, we are able to

understand the current state of the research and identify opportunities and directions for future research.

2.1 Methods

Search Strategy

An online database search was conducted in August 2015 using three online databases: Web of Science, PubMed, and PsycInfo. Broad keyword search terms used included: (1) Interruptions in healthcare, such as: "interruptions", "disruptions", "multitasking", "break-in-task"; and (2) A review or summary, such as: "a literature review", "a systematic review", "reappraisal", "review of research". A total of 727 papers were found based on the initial search. After removing duplicates, 575 papers remained for review.

Inclusion and Exclusion Criteria

The inclusion and exclusion criteria of this review were set to achieve the objectives of this chapter: to summarize the research gaps identified by the review papers and examine which gaps have already been addressed and which remain. To achieve these aims, we set the inclusion criteria to include papers that 1) were published in the last 10 years (after 2005) that systematically reviewed or critically summarized studies of interruptions in healthcare, and 2) identified one or more research gaps. The exclusion criteria were: (1) Papers that purely presented results of an empirical study; (2) Papers that did not identify any research gaps; (3) Papers in a domain other than healthcare, such as aviation or transportation; (4) Papers not in English; and (5) Papers that were not peer-

reviewed. Based on the inclusion and exclusion criteria, we further screened the 575 papers from the initial search. First, after removing papers earlier than 2005, 255 papers remained. Then, after reading titles and abstracts of the papers and comparing them with the inclusion and exclusion criteria, a total of 9 papers remained. Finally, an additional 6 papers were identified from the researcher's and colleague's collection of interruption papers as well as a reverse snow-ball method: reading the identified papers' references. A total of 15 papers were fully qualified for this review.

Data Analysis

First, we used a method-description approach to extract key data from the articles (Cooper, 1998), including the Year, Author, Title, Paper Type, Selection Criteria (related to the study setting, participants, and the types of interruptions), Purpose, and Key Findings. After that, we conducted an inductive coding process, identifying recurrent themes related to the aims of this research, i.e., the research gaps identified in the papers (Berg & Lune, 2011). Similar research gaps were combined into overarching themes. Finally, we summarized the findings across studies, examining which research gaps have been addressed and which have not. This three-step analytical process allowed for an integrated understanding of the research gaps related to interruptions in healthcare from various perspectives, thus advancing a new research agenda.

2.2 Results

Table 2.1 summarizes the 15 review or summary papers included in this review. Table 2.2 provides an overview of the gaps identified in the selected papers.

Overview of Included Papers

Among the 15 selected papers, 13 of them were systematic literature review papers, and two of them were summary papers. The majority of the papers in this review did not set special selection criteria for including specific participants, settings, or methods of interruption. Therefore, the reviews and summaries included studies of interruptions experienced by any healthcare professionals in any real clinical settings, including nurses, doctors, pharmacists, anesthesiologists, and administrative staff, as well as participants in experimental settings. Most of the papers also did not distinguish between studies related to interruptions mediated by people and/or devices, or interruptions due to operational failures. However, there were some exceptions. Four papers focused only on interruptions experienced by nurses (Biron et al., 2009; Hopkinson & Jennings, 2013; Monteiro et al., 2015; Raban & Westbrook, 2013). One paper specifically reviewed studies related to device-mediated interruptions (Wu et al., 2012). And one paper reviewed simulated interruption studies in laboratory settings (Li et al., 2012).

Research gaps identified in the reviews

Based on the inductive coding process, we identified seven major themes under which the research gaps were classified. In this section, each gap followed by if (and how) they were addressed is explained.

#1: Inconsistent definitions of interruption

The systematic reviews and summaries found that the definitions of the term ‘interruption’ in healthcare were inconsistent (Biron et al., 2009; Coiera, 2012; Grundgeiger & Sanderson, 2009; Hopkinson & Jennings, 2013; Sasangohar et al., 2012). This might be because the term ‘interruption’ in other domains, such as aviation and transportation, has a different meaning from the phenomenon of interruption studied in healthcare (Coiera, 2012). This might also be because similar concepts, such as interruptions, distractions, multi-tasking, and break-in-task were not clearly differentiated early on and thus were used interchangeably (Hopkinson & Jennings, 2013). Many definitions used in the interruption studies did not fully reflect the characteristics of an interruption. For example, they tended to be biased towards the negative effects of interruptions, ignoring the possible positive effects (Sasangohar et al., 2012). Also, the definitions focused on communication-oriented activities, neglecting some of the environmentally driven interruptions caused by background noise or operational failures (Biron et al., 2009). These inconsistencies made it difficult to compare and generalize results among studies (Grundgeiger & Sanderson, 2009; Sasangohar et al., 2012).

To address this research gap, reviewers made efforts to standardize the definition of interruption. For example, Sanderson & Grundgeiger (2015) defined an interruption as an event that leads a person to remove their attention fully but temporarily from a primary task to another task, before moving their attention back to the primary task. Werner & Holden (2015) expanded the notion of an interruption to define it as a process that could be caused by a sequence of events. Sanderson & Grundgeiger (2015)

differentiated the concepts of interruption, distraction and multitasking: Multitasking is the management of multiple threads of responsibilities, while a distraction temporarily diverts a person's attention to another task, and only if the person ceases the current task for a measurable amount of time does it become an interruption (Sanderson & Grundgeiger, 2015).

#2: Challenges of outcome measures

The systematic reviews and summaries found challenges in measuring the outcome of interruptions (Coiera, 2012; Monteiro et al., 2015; Rivera-Rodriguez & Karsh, 2010; Werner & Holden, 2015; Wu et al., 2012). In exploratory research using the method of direct observation, counting was a primary measure of interruptions (Coiera, 2012). However, the frequency of interruption occurrence actually cannot reflect the impact of the interruptions from a systems perspective (Rivera-Rodriguez & Karsh, 2010). Two other primary outcome measures were (1) the efficiency of workflow, which can be determined by the time on task, interruption lag, and resumption lag, and (2) patient safety, which can be determined task errors (Magrabi et al., 2011). However, these outcome measures were insensitive because interruption lags and resumption lags are often too transitory to be accurately measured, and human errors were generally not observable in complex healthcare work systems (Grundgeiger & Sanderson, 2009; Magrabi et al., 2011; Rivera-Rodriguez & Karsh, 2010).

Despite the insensitivity, Werner & Holden (2015) did find studies that measured the time spent on the original task, and identified errors made by interrupters and interruptees immediately after the interruption (Chisholm, Weaver, Whenmouth, & Giles,

2011; Westbrook, Woods, Rob, Dunsmuir, & Day, 2010). However, this research gap has not been fully addressed because the impact of interruptions is not limited to work efficiency and patient safety. The impacts might also include quality of patient care, patient satisfaction, as well as team- and organization-oriented effects (Monteiro et al., 2015; Werner & Holden, 2015; Wu et al., 2012), including distributed situation awareness, stress, and job satisfaction (Werner & Holden, 2015). According to the reviews and summaries, no study has examined these outcome measures.

#3: Limited empirical evidence for a causal relationship between interruptions and errors

The reviews and summaries found limited evidence to support a causal relationship between interruptions and human errors (Biron et al., 2009; Grundgeiger & Sanderson, 2009; Hopkinson & Jennings, 2013; Westbrook, 2014). Based on the findings in aviation and transportation, it was easy to extrapolate that an interruption in healthcare could also result in adverse events (Grundgeiger & Sanderson, 2009; Rivera-Rodriguez & Karsh, 2010). It was also perceived by both researchers and healthcare professionals that interruptions could contribute to human errors (Biron et al., 2009). However, the empirical evidence is limited because: (1) The healthcare work system is more heterogeneous, loosely coupled, and complex than many other work systems, making it difficult to collect data of adverse events and human errors (Grundgeiger & Sanderson, 2009); and (2) The effects of interruptions cannot be separated from other contributors to human errors, such as the culture, leadership, individual work performance, workload, and task complexity (Biron et al., 2009).

In several experimental studies, evidence of a causal relationship has been found. For example, according to Grundgeiger & Sanderson (2008), interruptions were associated with medical dispensing errors (Flynn et al., 1999). According to Westbrook (2014), the effect of interruptions on errors was found to be significant during a chemotherapy drug verification and administration process in a simulated setting (Prakash et al., 2014). Evidence of a causal relationship has also been found in naturalistic settings. According to Hopkinson et al. (2013), the relationship between interruptions and clinical errors was statistically significant during the medication administration process in a nursing work system based on an observational study (Westbrook et al., 2010).

#4: Lacking a holistic understanding of interruptions

The reviews and summaries found studies of interruptions in healthcare lacked a holistic understanding to reflect the dual-complexity of the process. During an interruption, the interrupter's system is connected with the interruptee's system; therefore, it is necessary to understand an interruption from both perspectives (Rivera-Rodriguez & Karsh, 2010). However, most of the interruption studies were conducted only from the perspective of the interruptees (Rivera-Rodriguez & Karsh, 2010). Single-sided studies can neglect some important implications of interruptions, such as the impact of interruptions to the interrupter's workflow. For example, an interruption may allow the interrupter to gather important information in time to proceed with an otherwise suspended task (Grundgeiger & Sanderson, 2009).

According to Sanderson & Grundgeiger (2015), field investigators rarely collected information regarding the interrupters in the interruption process, and the only exception was a nursing face-to-face interruption study in an intensive care setting (Rivera, 2014). In that study, the author investigated interrupter-interruptee interactions regarding the initiation and management of interruptions (Rivera, 2014). Although Rivera-Rodriguez & Karsh (2010) recommended studying interruptions using a systems approach, there were no other studies investigating interruptions systematically from both interrupter's and interruptee's perspective.

#5: Lacking an understanding the interruption's complexity

The reviews and summaries found studies of interruptions in healthcare lacked an understanding of the interruption's complexity, especially their possible values (Grundgeiger & Sanderson, 2009; Rivera-Rodriguez & Karsh, 2010; Sasangohar et al., 2012). While interruptions, especially those related to environment and operational failure, often have detrimental effects, organizational, technological and patient-related interruptions may have some positive benefits (Sasangohar et al., 2012). From a systems perspective, the interruptions could be goal-driven or value-added events (Rivera-Rodriguez & Karsh, 2010). Additionally, interruptions might be embedded within the healthcare professionals' workflow, proving essential for them to complete work-related activities (Monteiro et al., 2015). For example, an interrupter may achieve a goal by interrupting others (Rivera-Rodriguez & Karsh, 2010). However, most studies focused only on the detrimental effects of interruptions, which resulted in reductionist interventions to eliminate or block all the interruptions in healthcare settings, including

the goal-driven or purposeful interruptions (Grundgeiger & Sanderson, 2009; Rivera-Rodriguez & Karsh, 2010; Sasangohar et al., 2012).

Value-added interruptions have been investigated in some recent studies. For example, according to Hopkinson and colleagues (2013), among 5000 interruptions experienced by pediatric nurses, 11% of them can be categorized as positive interruptions (11%) (McGillis Hall et al., 2010). According to Hayes and colleagues (2015), it was found that interruptions may improve patient care and safety in such a situation that a patient was the interrupter and questioned the nurse to determine the accuracy of medications during the medication administration process (McGillis Hall, Pedersen, & Fairley, 2010). According to Sanderson & Grundgeiger (2015), it was found that an interruption can be both positve and negative at the same time, for example, an interruption might be positive to the interrupter regarding communication efficiency and their patients regarding safety, but negative to the interruptee regarding the disruptiveness of workflow (Rivera, 2014). However, there were no other studies investigating the interruption complexity in more depth, and it is still unclear how interruptions may influence nursing work positively, neutrally, and/or negatively at different situations.

#6: Insufficient conceptualization of interruptions in complex real-world environments

The reviews and summaries found interruptions in complex real-world environments were not reflected in researchers' conceptualizations (Coiera, 2012; Magrabi et al., 2011; Werner & Holden, 2015; Westbrook et al., 2010). Interruptions may be deconstructed into several phases if simulated in an experimental setting, as shown in the time-course of an interruption (Li et al., 2012). However, interruptions in the real

world are context specific (Coiera, 2012). First, interruptions in the real world may not always be a single event; they could be a process or a flow of multiple unfolding events (Werner & Holden, 2015; Westbrook et al., 2010). Second, system factors surrounding the interruption, such as the work environment, task, organization and culture, are all related and interact with one another within the work system shaping the impacts of interruptions (Magrabi et al., 2011; Werner & Holden, 2015).

In the existing research, these context-specific characteristics of interruptions have not been sufficiently conceptualized. Therefore, there was no evidence that this gap has been addressed. Werner & Holden (2015) presented a sociotechnical system model as a first step towards addressing this gap. Based on this model, interruptions can be described as unfolded processes influenced by multiple structural factors, such as environmental factors and task characteristics.

#7: Ineffective design and insufficient evaluation of interventions

The reviews and summaries found the design of interventions was ineffective and the evaluation of the interventions was insufficient (Hayes et al., 2015; Hopkinson & Jennings, 2013; Raban & Westbrook, 2013; Westbrook, 2014). From a systems perspective, effective interventions should support interruption management, encouraging value-added interruptions and mitigating non-value-added interruptions (Rivera-Rodriguez & Karsh, 2010). However, available interventions were limited to the mitigation of interruptions, through such methods as “quiet zones” and “no interruption vests” (Hayes et al., 2015; Hopkinson & Jennings, 2013; Raban & Westbrook, 2013).

These interventions were evaluated using a comparison of pre- and post-implementation (Westbrook, 2014).

Although the effectiveness to mitigate interruptions has been validated, there was no evidence on sustainability (Hayes et al., 2015), and no study sought to understand the unintended consequences of interventions, i.e., the elimination of interruptions that might be necessary in the workflow (Raban & Westbrook, 2013). According to Wu and colleagues (2012), the implementation of communication devices would be a potential intervention that could improve the metrics of communication, support workflow, provide flexibility, and reduce the time for interruptions (Breslin, Greskovich, & Turisco, 2004; Richardson & Ash, 2010). However, their effectiveness for supporting interruptions still need to be investigated and evaluated (Wu et al., 2012).

Table 2.1: Literature Review Paper Summary

	Year	Author	Title	Paper Type	Selection Criteria	Purpose	Key Findings
1	2009	Grundgeiger & Sanderson	Interruptions in healthcare: Theoretical views	Literature Review (35 studies)	Interruption studies in care and medication dispensing settings	Review the evidence for a causal relationship between interruptions and adverse events.	The causal relationship between interruptions and medical errors was weak. Inconsistent definitions of interruption abounded the studies. Interruptions in healthcare and their impacts were complex.
2	2009	Biron et al.	Work interruptions and their contribution to medication administration errors: An evidence review	Literature Review (23 studies)	Interruption studies in clinical settings that involve the nurse's activity of medication administration.	Review the evidence for rates, characteristics and the contributions of work interruptions	The rate of work interruptions during medication administration was 6.7 per hour for nurses in clinical settings. Work interruptions were mostly initiated by nurses themselves through face-to-face interactions. There was limited empirical evidence on the contribution of interruptions to medication administration errors.
3	2010	Rivera-Rodriguez & Karsh	Interruptions and distractions in healthcare: review and reappraisal	Literature Review (33 studies)	Interruption studies in both clinical settings and laboratory settings	Review the current statue of interruptions research in healthcare and identify gaps	Interruptions in healthcare occured with high frequency indicative of the need for constant communication and coordination in healthcare. Many interruptions may be necessary for safe, high-quality care, especially from the interrupter's perspective; however, existing interruption research rarely covered the perspectives of both interrupters and interruptees.
4	2011	Margrabi et al.	Challenges in measuring the impact of interruption on patient safety and workflow outcomes	Literature Review (19 studies)	Interruptions in both laboratory settings and emergency and intensive care	Review to examine the problems of studying interruptions in healthcare	Interruptions had multiple variables, such as the type of task (both primary and interrupting task), point of interruption, duration of interruption, similarity of interruptive task to primary task, modality of interruption, environmental cues and interruption handling strategies. The outcome may be measured by errors, the time on task, interruption lag, and resumption lag.
5	2011	Li et al.	A systematic review of the psychological literature on interruption and its patient safety implications	Literature Review (63 studies)	Interruptions in laboratory settings only	Review to understand the complex effects of interruption in healthcare based on a set of variables	Variables that influenced interruption effects were identified, such as the interruption position, interruption similarity, interruption handling strategies, interruption modality, work memory load, practice/experience, interruption frequency, interruption complexity, primary task complexity, prior knowledge of interruption, interruption duration, and cue availability.

6	2012	Coiera	The science of interruption	Opinion paper	General interruption studies	To provide an explicit explanation of the challenges of interruption research in healthcare	Three major challenges in the science of interruption: method, theory, and translation.
7	2012	Sasangohar et al.	Not all interruptions are created equal: Positive interruptions in healthcare	Literature Review (22 studies)	General interruption studies	Review the definitions of interruption and present a classification of sources of interruptions	The majority of environmental interruptions likely had detrimental effects on performance. However, the majority of organizational, technological, and patient-related interruptions had positive effects on the main task and patient safety. There were inconsistencies in defining interruptions in the current literature, of which the majority were biased towards their negative effects.
8	2012	Wu et al.	Effects of clinical communication interventions in hospitals: A systematic review of information and communication technology adoptions for improved communication between clinicians	Literature Review (18 studies)	Interruptions mediated by devices only, such as alpha pager, HCDs, mobile phones, smartphones, task management systems, and display-based paging system.	Review of the literature to identify, describe, and assess the implementation of information and communication technology on communication and patient outcomes.	There was limited evidence suggesting the effectiveness of communication devices regarding their use for interruptions. Unintended consequences included long response time, lack of response, reliability issues, increased frequency of interruptions, and the loss of richness in communication compared to face-to-face.
9	2013	Hopkinson & Jennings	Interruptions during nurses' work: A state-of-the-science review	Literature Review (31 studies)	Interruption studies in acute care settings that involve the activities of nurses.	Review to examine empirical evidence of interruption research and their current state.	The studies of interruptions remained at a descriptive and exploratory level. There were several inconsistencies among the studies, such as the ways to count and classify interruptions. Limited evidence linked the interruptions with outcomes. The effects of interruptions on teamwork were not measured.
10	2013	Raban & Westbrook	Are interventions to reduce interruptions and errors during medication administration effective? A systematic	Literature Review (10 studies)	Interruption studies in clinical settings with the activity of medication administration	Review to assess evidence of the effectiveness of interventions for reducing interruptions during medication administration and errors.	There was weak evidence of the effectiveness of interventions to significantly reduce interruption rates and very limited evidence of their effectiveness to reduce errors.

			review				
11	2014	Westbrook	Interruptions and multi-tasking: moving the research agenda in new directions	Literature Summary	General interruption studies	To provide a summary of the productive area and limitations of the research of interruptions in healthcare	The evidence for a direct link between interruptions and errors was sparse. The studies to test effective interventions for reducing interruptions and error were rich in laboratory settings; however, the evidence was limited in real settings. Sociotechnical context has begun to be focus; however, there were methodological and theoretical challenges.
12	2015	Hayes et al.	Medication errors in hospitals: A literature review of disruptions to nursing practice during medication administration	Literature Review (19 studies)	Interruption studies in educational settings that involve the nurse's activity of medication administration.	Review to explore what is known about interruptions and distractions during medication administration in the context of undergraduate nurse education.	There was limited knowledge about how nurses manage interruptions during medication administration. The were opportunities to explore a program to assist undergraduate nurses in learning interruption management.
13	2015	Monteiro et al.	Interruptions of nurses' activities and patient safety: an integrative literature review	Literature Review (29 papers)	Interruption studies in clinical settings that involve nurses' activities.	Review to identify characteristics of the interruption nurses experience and the implications of interruptions on patient safety.	Interruptions can be a harmful factor for patient safety due to their impact on performance and the decision-making process; however, they did not always lead to adverse events and may have a positive impact on performance. Environmental factors and human factors may need to be considered to understand interruptions.
14	2015	Sanderson & Grundgeiger	How do interruptions affect clinician performance in healthcare? Negotiating fidelity, control, and potential generalizability in the search for answers	Literature Review (12 studies)	General interruption studies	To understand the fidelity, control and potential generalizability in the representative papers, and uncover the burden and problem of interruptions and distractions research in healthcare.	The principal challenge of field studies in interruption research was the control of variables. Researchers may achieve a high level of control by theory-guided field research. Other types of research could also achieve higher rigor.
15	2015	Werner & Holden	Interruptions in the wild: Development of a sociotechnical systems model of interruptions in the	Literature Review (15 studies)	Interruption studies in the context of ED only	Review to understand which sociotechnical system characteristics are investigated, how is the interruption process conceptualized, and	A sociotechnical model of interruptions was developed to conceptualize the complexity of interruptions in ED. This model reflected: Interruption as a process, not a single event; Interruption can include a singular task or multiple unfolding events; Interruption was shaped by the sociotechnical system, composed of an interacting set of

			emergency department through a systematic review			what are the outcomes of interruptions	structural components; Interruptions can have multiple potential proximal and distal outcomes, including multiple individuals, such as interrupters and interruptees.

Table 2.2: Gaps Identified in Systematic Reviews and Summaries

	Inconsistent definitions of interruption	Challenges of outcome measures	Limited empirical evidence for a causal relationship between interruptions and errors	Lacking a holistic understanding of interruptions	Lacking an understanding of the interruption complexity	Insufficient conceptualization of interruptions in the real-world context	Inefficient design and insufficient evaluation of interventions
Grundgeiger & Sanderson (2009)	X		X	X	X		
Biron, et al. (2009)	X		X				
Rivera-Rodriguez & Karsh (2010)		X		X	X		
Margrabi et al. (2011)						X	
Li et al. (2011)							
Coiera (2012)	X	X				X	
Sasangohar et al. (2012)	X				X		
Wu et al. (2012)		X					
Hopkinson & Jennings (2013)	X		X				X
Raban & Westbrook (2013)							X
Westbrook (2014)			X			X	X
Hayes et al. (2015)							X
Monteiro et al. (2015)		X					
Sanderson & Grundgeiger (2015)							
Werner & Holden (2015)		X				X	

2.3 Discussion

The research of interruptions in healthcare has been growing steadily in recent years. Many aspects related to interruptions have been explored and some research gaps identified in previous reviews and summaries have been addressed. For example, the definition of interruption has been standardized (Sanderson & Grundgeiger, 2015). It has also been differentiated from other similar concepts (e.g., distractions) (Sanderson & Grundgeiger, 2015; Werner & Holden, 2015). The outcomes of interruptions related to workflow efficiency and patient safety have been examined (Flynn et al., 1999; Prakash et al., 2014). A causal relationship between interruptions and human errors has been established in the context of the medication administration process in natural healthcare settings (Westbrook et al., 2010).

However, big gaps still exist in the research of interruptions (See Table 2.3). As shown in Table 2.3, the focus of interruption research was primarily on the detrimental effects to the interruptees and the unit of analysis is limited to isolated interruption events, not properly reflecting their complexity. Previous reviewers have made claims that interruptions can actually have positive, neutral, and negative impacts on both interrupters and interruptees (Rivera-Rodriguez & Karsh, 2010). The interruptions can be caused by a series of events in the real world context (Westbrook, 2014). They can impact multiple team members who share distributed cognition in the work environment (Werner & Holden, 2015; Westbrook, 2014). However, studies of interruption in healthcare have not reflected these complexities.

Table 2.3: Comparison Research Focus and Research Gaps

	Research focus	Research gaps
1	The impact of interruptions on interruptees only	Interruptions may have impact on both interrupters and interruptees.
2	Only the detrimental effects of interruptions	Interruptions can be value-added, non-value added or neutral.
3	The unit of analysis as a single event	Interruptions can occur as a series of events
4	Limit the impact of interruptions at the level of individuals	Interruptions can impact multiple individuals who share distributed cognition
5	Studying the impact based on only the characteristics and contents of interruptions	Context shaped by system factors can also impact interruption dynamics

Additionally, as shown in Table 2.3, the dynamic, interactive, and complex context of the healthcare work system, in which interruptions occur, has not been investigated in the current research. We agree with Werner & Holden (2015) that a combination of work system factors in the interruption process may act together to influence the decisions and performance. These system factors may be related to individual/team characteristics, the human-system interface, the nature of work or tasks, the physical work environment, the organizational culture and infrastructure, and the external environment (Carayon et al., 2006; Holden et al., 2013).

We suggest the research of interruptions in healthcare be guided by theoretical frameworks that provide a systems perspective, which may shift our focus from the impact of a single system factor in the interruption process to the connections and interactions of system factors (Wilson, 2000), to uncover the complexity of interruptions in the real world. A systems perspective is based on the sociotechnical systems theory (Trist & Bamforth, 1951), and considers the compatibility of inputs within the work

system (Carayon et al., 2006). Specifically, the meso-ergonomics paradigm and activity theory are the potential frameworks. The meso-ergonomics paradigm bridges micro- and macro-aspects of the system (Karsh, Waterson, & Holden, 2014) and considers causal paths and mechanisms across different levels in the sociotechnical work system (Karsh, 2006; Rivera-Rodriguez et al., 2013). Activity theory is a phenomenological framework, connecting the subjects with the object through a mediating tool in the real-world context (Engeström, 2000). The two frameworks complement one another to address the research gaps of interruptions in healthcare: (1) Multidimensional complexity of interruptions can be uncovered by considering the impact to both interrupters and interruptees transcending from human cognition to the entire team and organization; and (2) The role of context can be uncovered by incorporating the investigation of the social and cultural subsystem into interruption research.

The study presented in this chapter is unique in reviewing the previous systematic reviews and summaries of interruption studies. This uniqueness may also result in a limitation to this study: recent studies may not have been included in the reviews and summaries. For example, Werner and Holden (2015) identified several interruption studies meeting their review inclusion criteria that were published after their literature search. However, to compensate for this limitation, we reviewed studies that have been published since each of the latest reviews, and found that the research gaps identified in this review still exist.

2.4 Conclusion

Future research of interruptions in healthcare must continue to address remaining gaps that still exist as identified in previous reviews. Researchers need to understand the multidimensional complexities of interruptions in the real world using systems approach. Because of the implementation of HCDs, it is expected that the complexity would be further increased. To understand the complexity in the real world, in this dissertation, a preliminary study was conducted to understand the differences between HCD-medicated and face-to-face interruption dynamics in the acute care setting (Chapter 3). A follow-up study was conducted to explore the impact of system factors on HCD interruption dynamics, as well as their influence on nurses' decisions and performance regarding the use of HCDs (Chapter 4).

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CHAPTER 3: AN OBSERVATIONAL STUDY OF HANDS-FREE COMMUNICATION DEVICES MEDIATED INTERRUPTION DYNAMICS IN A NURSING WORK SYSTEM

This chapter presents a final version of a manuscript titled: "An Observational Study of Hands-free Communication Devices Mediated Interruption Dynamics in a Nursing Work System" that was published in Health Policy and Technology (Yang & Rivera, 2015). The formatting was changed to match to dissertation.

3.1 Paper Title and Authors

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3.2 Abstract

Objective: The objective of this study is to examine how the integration of Hands-free Communication Devices (HCDs) differentiates the interruption dynamics from the existing knowledge of face-to-face interruptions in a nursing work system.

Introduction: Many aspects of nursing workflow and work efficiency have been improved with the implementation of HCDs; however, the frequency of interruptions in the workplace has not been reduced. The complexity of HCD-mediated interruption dynamics needs to be studied using a Socio-technical Systems (STS) approach in order to holistically understand the problem and their effects.

Methods: We conducted field observations in the acute care setting. A total of 12 nurses across two units were selected as participants in this study. Each participant was shadowed for 2.5 hours totaling 30 hours of observations. We iteratively coded the data into overarching themes using content analysis.

Results: We determined three overarching themes: (1) assessment prior to interrupting, (2) interruption content delivery, and (3) response to interruptions. Based the coding structure and the observation events in each theme, we identified facilitators and barriers for nursing work related to the HCD-mediated interruption dynamics. The facilitators included "intact workflow continuity", "reduced time pressure", and "increased flexibility to respond to interruptions". The barriers included "interrupter-oriented nature", "interruptee's overprotection of workflow", "delay of information delivery", and "inaccuracy of information communicated".

Conclusion: The findings of this study reflect the unique role of HCDs in affecting interruption dynamics and nursing work. Based on the findings, we proposed system design recommendations, organizational-level interventions, and policy suggestions.

3.3 Introduction

Nurses' work is complicated, as they need to stay informed with real-time updates regarding patient information for effective task-planning, care coordination, and patient-related problem-solving (Manser, 2009; Tucker & Spear, 2006). Those tasks are generally completed in various locations, such as patient rooms, hallways, nursing stations, offices, and front desks. Team communication is an important component in the nursing work systems (Coiera & Tombs, 1998). An influx of pervasive communication technologies have been implemented to support team communication, such as telephones, mobile phones, pagers, hand-held personal digital assistants, as well as wearable Hands-free Communication Devices (HCDs) (Wu et al., 2012). Research has shown in systems with HCDs, nurses' walk distance and time spent on communication has been reduced (Breslin, Greskovich, & Turisco, 2004; Ernst, Weiss, & Reitsema, 2013; Kuruzovich, Angst, Faraj, & Agarwal, 2008; Pemmasani, Paget, van Woerden, Minamareddy, & Pemmasani, 2014; Vandenkerkhof, Hall, Wilson, Gay, & Duhn, 2009). Therefore, HCDs are promising in improving nursing workflow, communication efficiency, and continuity of patient care.

In the current US market, the main HCDs used in inpatient settings are Vocera. Wearing a Vocera around their necks, nurses can simply touch a button on the device and say the name of the intended recipient to get a synchronized call connected. When a nurse

receives a call from the Vocera, the device notifies them of the caller's name. To get a Vocera-mediated communication connected, nurses do not need to look away from their primary tasks. Theoretically, humans perform better when processing stimuli in different modalities, such as a visual stimulus and an auditory stimulus, as opposed to stimuli in the same modality, such as two simultaneous visual stimuli (Wickens, 2008). Therefore, HCDs are promising in facilitating the improvement of nursing work performance and patient safety. When a Vocera call comes in, the user can either accept the call immediately, or delay the acceptance of the call, depending on their willingness and current interruptibility. If a call is connected, the conversation can be heard from either a speakerphone on the Vocera or an earpiece connected by a cord. If a call is delayed, the caller will be transferred to the user's voice mailbox, without the need to further interrupt the receiver. Therefore, HCDs provides extra flexibility to the nurses.

Regardless of the promising benefits of HCDs, they do create more interruptions in the healthcare work system (Ernst et al., 2013). Interruptions are defined as a secondary, unplanned and unexpected task that discontinues a healthcare professional's primary workflow (Brixey, 2008). Interruptions are a common occurrence in healthcare systems (Rivera-Rodriguez & Karsh, 2010) and the nursing work environment is an interruption-laden workplace (Brixey et al., 2005). The rate of interruptions is estimated at 6.7 per hour based on an evidence-based review of 14 studies (Biron, Loiselle, & Lavoie-Tremblay, 2009). Existing research of interruptions in healthcare has primarily focused on human face-to-face interruptions, such as those initiated by staff (Rivera, 2014) or patients (Hedberg & Larsson, 2004), and technology-related interruptions, such

as those mediated or created by cell phones (Avrahami, Gergle, Hudson, & Kiesler, 2007; Grandhi & Jones, 2009), health information technology (Patterson, Rogers, Chapman, & Render, 2006), alarms (Tang et al., 2007), or operational failures (Tucker & Spear, 2006). Findings suggested a significant association of interruptions with the incidence of procedural failures and clinical errors (Westbrook, Woods, Rob, Dunsmuir, & Day, 2010), and their role as latent contributors to adverse events and medical errors (Alvarez & Coiera, 2006; Flynn et al., 1999; Institute of Medicine, 2000; Wiegmann, ElBardissi, Dearani, Daly, & Sundt, 2007).

The effects of interruptions in healthcare on human performance and decision-making have been studied from the psychological and cognitive perspectives (Grundgeiger & Sanderson, 2009; Li, Magrabi, & Coiera, 2012). Although people have natural abilities to dynamically adapt to an interruption-laden work environment, interruptions have negative impacts on performance, causing stress, mistakes, and reduced efficiency (McFarlane & Latorella, 2002). The negative impacts are mainly due to two reasons. First, the occurrence of an interruption often requires human cognitive efforts and attentional resources to process a secondary task (Speier, Valacich, & Vessey, 1999; Wickens, Hollands, Banbury, & Parasuraman, 2013). With the additional information to be processed, if the cognitive demand exceeds the person's capability, human performance and decision-making will be negatively affected (Wickens et al., 2013). Second, after diverting attention from the primary task to the secondary task, it may be challenging for the person to draw on retrieval cues in their prospective memory and resume their primary task, especially when the interrupting task is similar to the

primary task, complicated, or frequent (Cades, Trafton, Boehm-Davis, & Monk, 2007; Grundgeiger & Sanderson, 2009; McFarlane & Latorella, 2002; Ratwani, Andrews, McCurry, & Trafton, 2007; Westbrook, et al., 2010).

The research of HCD in healthcare is in its infancy (Wu et al., 2012), and has primarily focused only on the interruption frequency, user satisfaction, quality of communication, and their reliability (Breslin et al., 2004; Ernst et al., 2013; Jacques, France, Pilla, Lai, & Higgins, 2006). This research area is still lacking an integrated understanding of HCD-mediated interruptions and their effects. Using a Socio-technical Systems (STS) approach can provide a holistic representation of this interruption problem space. A STS approach, such as macroergonomics, considers the compatibility of system inputs within the work system: people, tools and technology, tasks, physical environment, and organization elements (Carayon et al., 2006); and focuses on the joint optimization of the social and technical subsystems (Hendrick & Kleiner, 2001). Building upon our knowledge of the complexities during nursing face-to-face interruptions (Rivera, 2014), and using the STS approach, we define HCD-mediated Interruption Dynamics (HCDMID) as a combination of contextual factors influencing nursing work performance and decision-making during the entire HCD-mediated interruption process, starting from the interrupter initiating the interruption, to the interruption content being communicated, and finally to the interruptee managing the interruption. Multiple contextual factors, including both interrupters (and all of their characteristics) and the interruptees (and all of their characteristics), the primary task, interruption timing, frequency, modality, and handling strategies, may be involved in the interruption dynamics to positively or

negatively affect nursing work (Karsh, Weinger, Abbott, & Wears, 2010; Li, Magrabi, & Coiera, 2012; Rivera-Rodriguez & Karsh, 2010).

The purpose of this study is to examine how the integration of Hands-free Communication Devices (HCDs) differentiates the interruption dynamics from the existing knowledge of face-to-face interruptions in a nursing work system. We expect our findings can inform product design improvements, organizational-level interventions, and policy suggestions to address barriers in the nursing work system brought by the HCDs.

3.4 Methods

We conducted a field study to interpret the phenomenon of HCD-mediated interruption dynamics. Qualitative research, such as observation, is powerful in deeply understanding behaviors and experiences of the interested populations (Creswell, 2012). Based on a comprehensive understanding of the phenomenon, we are able to elucidate the complexities of HCD-mediated interruption dynamics.

Research settings

The study was conducted in a hospital located in the southeastern United States. It was approved by both the university and hospital Institutional Review Boards. The hospital is a 746-bed acute care medical-surgical facility. Two acute care units were selected as the research setting. They were geographically similar with a main meeting office and small decentralized nursing stations for individual nurses located outside the patient rooms (Figure 3.1). Each nurse had a computer on wheels that could be moved in

and out the patient rooms. During a work shift, each nurse was typically responsible for taking care of 3-4 patients.

Participants

Nurse participants were recruited through convenience sampling, which depended on the observation time and the nurses working on the units during that time. There was no specific exclusion for participation, and all the nurses working in the two acute care units were potential participants. When the observer arrived at one of the units, the nurse manager randomly assigned a nurse participant, who at that point was available for a short informed consent session. In both of the units, each nurse was equipped with a HCD.

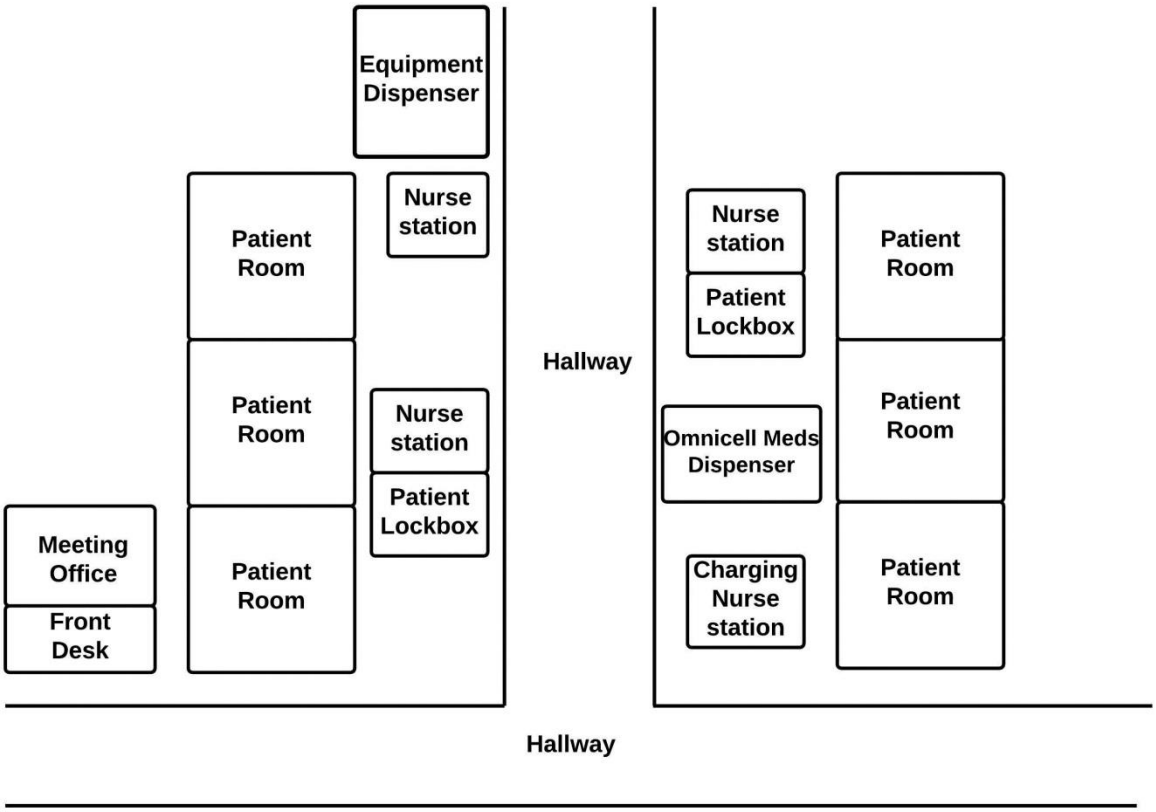

Figure 3.1: Study site layout

Procedure

Ten hours of general observations was conducted to get familiar with the acute care units. We identified that medication administration occurred most often at 7:30 am, 3:30 pm, and 7:00 pm on these units, and structured our observations around those times as medication administration has been identified as a critical process for patient safety (Leape et al., 1995). Following the general observations, we conducted formal observations until data saturation occurred: 12 nurses were observed; 1 nurse per observation period for 2.5 hours at a time for a total observation time of 30 hours. At the

beginning of each observation, the participant was provided with an information sheet and verbal consent was obtained. During observations, the observer (YY) shadowed the participant. The observation was structured by the communication observation method (Spencer, Logan, & Coiera, 2002). The observer recorded what and how nurses performed tasks in their work environment, and the contextual information of both face-to-face and HCD-mediated interruptions. Contextual information included: interruption source/receiver, the technology used, the primary task, the interrupting task, response, and time and location of interruption occurrence. Informal conversations with nurses occurred only when the nurses proactively talked with the observer, and we made every effort to minimize intrusion during observation. Immediately after the observation, the observer transcribed his field notes into an electronic file and during that process expanded on his field notes, to include any missing contextual information he experienced while collecting the data. Additional comments were made when the observer found it necessary to describe the context in more detail.

Analysis

Following the general principles of qualitative data analysis, we aggregated and systematically reviewed the data. We reflected on the data by comparing them with a previous study of face-to-face interruptions in a nursing work system (Rivera, 2014). During the comparison process, we determined overarching thematic categories that represent the distinguishing differences between human face-to-face and HCD-mediated interruption dynamics. Then, in NVivo 10© (QSR International Pty Ltd., Melbourne Australia), we followed an open coding process to deductively and selectively attach

observational events, which captured patterns or trends related to the theme and distinguished them from the rest of the data, to the overarching thematic categories (Strauss & Corbin, 1990). One researcher (YY) started the content analysis process first and then another researcher (AJR) reviewed the coding structure. Although the initial agreement was high, we held open discussions to solve disagreements. We refined the overarching thematic categories and open codes in three rounds until consensus was reached.

3.5 Results

Our data suggests three overarching thematic categories that represent distinguishing differences between face-to-face and HCD-mediated interruption dynamics. The first theme, *assessment prior to interrupting*, describes how the interrupter initiates an interruption, such as a trigger, delay or stop. The second theme, *interruption content delivery*, describes how efficiently information is communicated from the interrupter to the interruptee through HCDs. The third theme, *response to interruptions*, describes how the interruptee manages the interruption when that occurs, such as attending to interrupting tasks, multitasking, delaying or rejection. The comparison of interruption dynamics in each theme is summarized in Table 3.1.

Table 3.1: Interruption Dynamics Comparison

	Face-to-face	HCD
Theme 1: Assessment prior to interrupting	Interrupter has the opportunity to thoroughly assess the interruptee's interruptibility and decide the best time to interrupt. However, time pressure may hinder a thorough assessment.	Due to being in separate locations, the interrupter lacks the opportunity to assess the interruptee's interruptibility. Interruptions are mostly initiated based on the needs of interrupter.
Theme 2: Interruption content delivery	It takes time to find the right person, but once found, the interruption content is delivered rapidly and with clarity, providing the interruptee with affective visual and auditory cues.	Finding the right person is done quickly by clicking a button and saying the intended recipient's name. However, there is a connection lag, which slows the interruption content delivery. Also, the interruption lacks visual cues and auditory cues are muted.
Theme 3: Response to interruptions	Interruptee tends to respond to interrupting tasks immediately, especially for those that are time-sensitive.	Interruptee can decline or delay a call from HCD, so that their workflow can be kept to a large extent continuous. When the interruptee accepts a call, they may continue the primary task, and attend to the interrupting tasks at a later time.

Assessment prior to interrupting

For face-to-face interruptions, prior to interrupting others, the interrupter has opportunities to thoroughly assess the interruptee's interruptibility and decide when to interrupt. Interruptibility includes the interruptee's cognitive and social state, as well as the willingness to be interrupted (Rivera, 2014). Based on the assessment, nurses can create a high-level of situation awareness (SA) regarding the possible disruptiveness to the interruptee's workflow. SA is defined as the perception of elements in the environment with respect to time and space, the comprehension of the elements' meanings, and the projections of the future (Endsley, 1988). With a high-level SA, nurses are more likely to initiate a face-to-face interruption at an appropriate time, delaying the interruption if the interruptee's interruptibility is low. For example (1): *A nurse intends to*

ask another nurse a question, that nurse is in the patient's room preparing medications for administration. She waits at the door and asks the question when the nurse finishes administering the medications to the patient.

Besides interruptibility, nurses also assess the necessity for an immediate interruption based on the interruptee's primary task. At times, a timely interruption is necessary for facilitating nursing teamwork, enhancing the quality of an activity, or correcting an error. For example (2): *A junior nurse administers an intravenous (IV) medication. When she connects the syringe to the IV pump, a senior nurse interrupts to remind her of the correct procedure.* Nursing work involves a broad spectrum of tasks, including medication preparation and administration, direct patient care, care coordination, nurse-patient/family communication, documentation, etc. (Tucker & Spear, 2006). Some tasks have quick deadlines, requiring nurses to complete them as soon as possible. Due to this time pressure, they may not always be able to make a thorough interruptibility assessment before interrupting others. For example (3): *A nurse cannot find cotton sticks in the patient room nor in the Supply Management Cabinet. She saw a nurse next to her and immediately interrupts the nurse to ask if she has any idea where they could be.*

In contrast to the face-to-face interruptions, prior to interrupting others using HCD, the interrupter can hardly make an assessment of the interruptee's interruptibility. The two systems (interrupter and interruptee) are not in the same physical location; therefore, gathering cues to develop SA is not as easy as it is with face-to-face interruptions, resulting in low SA. It is likely that HCD-mediated interruptions occur to

fulfill the needs of the interrupter, for example (4): *Before administering a medication, the nurse needs to verify the patient's blood sugar. She calls the nursing assistant and acquires the value.* However, this communication usually lacks the consideration of the interruptee's interruptibility. Therefore, interruptions via HCD may happen at a time when they should be delayed or should not occur altogether. For example (5): *With an intent to report a patient's blood sugar reading to the charge nurse, a nurse initiates a call using Vocera, however, the charge nurse is too busy to accept the call so the call is rejected.*

Interruption content delivery

For face-to-face interruptions, finding the intended person may take time and need significant travel. For example (6): *A nurse at the beginning of her shift does not carry a Vocera with her. She has to travel to another patient room, finds another nurse in that room and asks a question.* However, once the interrupter and interruptee are in the same vicinity and the interruptee's attention is diverted to the interrupter, the interruption content can be communicated rapidly and with clarity. Additionally, interruptees can even anticipate the interruption content and urgency before it is delivered in its entirety. The anticipation relies on the obvious auditory/visual cues, such as the tones, facial expressions, and body language of the interrupter, often driven by time pressure, anxiety, or worry. These affective cues speed up the interruption content delivery. For example (7): *A nursing assistant shouts to the nurse from a distance in a loud and nervous voice. Due to the intensity and nervous tones projected by the nursing assistant, on the onset of the interruption, the nurse immediately realizes and expects there is some type of an*

emergency. As the message is fully communicated, the nurse finds out from the nursing assistant that a patient is disoriented and has low oxygen saturation.

In contrast to face-to-face interruptions, using HCD to interrupt others saves on travel as the interrupter can connect remotely to communicate with the coworkers. For example (8): *A nurse uses Vocera to notify operating room staff that a patient will be ready to be transported to the pre-operating unit in 10 minutes.* However, interruption content may come across relatively slowly via HCD. The connection process takes time because there is an obvious lag after initiating the call. Also, the interrupter has to wait for the interruptee to agree to connect the call. The following example illustrates the entire procedure for the interruption content delivery via HCD (9): *A nurse has a question. She touches the button on the Vocera, and says the name of another nurse she intends to reach. The other nurse's Vocera sounds and reads the name of the interrupting nurse out loud. After being connected, the interrupting nurse describes the question in its entirety.* The interruptee can hardly anticipate the content of an interruption when communicating using HCD, because they have no way of perceiving any visual cues from the interrupter. The auditory cues, such as expressions of urgency, may, to an extent, be eliminated or reduced as the message is being communicated. This is due to the signal process programming of technological communication devices, where auditory tones and pitches, which contain emotionally driven fluctuation and act as cues in face-to-face conversations, are balanced out, creating a more mono-tone voice projection (Casali, 2012).

Technological issues of HCD compound with the contextual factors and environmental interference resulting in the inefficiency of interruption content delivery. HCD sometimes inaccurately connects the interrupter to an unintended recipient. For example, it may not recognize the voice command initiated by interrupter. For example (10): *A charge nurse who has an accent says the name of another nurse after touching the button on the Vocera. Vocera confirms with an incorrect name. She tries to say the name again, but Vocera still does not recognize the name correctly. She gives up and goes to the patient room to find the intended nurse.* Additionally, depending on the influence of the environment and signal, voice recognition and communication function of HCD may not function perfectly, and events like the following can occur: (11) *The nurse interrupter is not being connected to the appropriate interruptee*; (12) *The quality of the sound may be so poor that the nurse interruptee is not able to hear exactly what the caller intends to say*; (13) *The nurse interruptee commands to decline the call but the call connects anyways*; and (14) *Another person, such as a patient, who is not wearing the HCD, says "yes" at the exact same time when a Vocera call comes in, and coincidently, the patient's command triggers the call to get connected.*

Response to interruptions

For face-to-face interruptions, the interruptee tends to respond to interrupting tasks in a timely manner. Even if some interruptions occur at inappropriate times or locations, most nurses still respond to a variety of interrupting tasks without delay. Based on observations, several types of interruptions were responded to more immediately, including: being a witness of controlled medications, answering questions from

physicians and patient/family, providing help and information, correcting an incorrect work performance, etc. For example (15): *A nurse asks another nurse to be a witness for a controlled medication draw-up. The other nurse agrees to witness, immediately stops charting, carefully checks the medication name and dose, and has her badge scanned by the nurse*. Similar events occurred repeatedly during observations. When they occurred, the primary workflow of the interrupted nurse may be disrupted and opportunities for errors may be increased.

In contrast to face-to-face interruptions, when managing interruptions via HCD, interruptees appear more comfortable rejecting or delaying a call if they are really busy or completing a task that should not be interrupted, e.g., medication administration. For example (16): *A nurse receives a Vocera call while administering medication to her patient. She hears the name of the caller, and says "no" to decline the call. She continues with her workflow and returns the call at a later time.* Sometime, they may also delay the message of the interruption by accepting the call and stating that she/he is currently busy and will call back soon. In both cases, the workflow of the primary task has been kept to a large extent continuous, in comparison to a face-to-face interruption. When the interruptibility is determined high, the interruptee may decide to accept the call from the HCD. In this case, while communicating with the interrupter, interruptees may still continue the primary task, and attend to the interrupting tasks at a later time. For example (17): *A nurse receives a call via Vocera while she is charting. The nurse accepts the call and is notified that a patient's surgery is finished and the patient will be transported back to the patient room. While accepting and acknowledging the information, the nurse never*

stops charting. After a while, she goes to the patient room to check with on patient. However, when the interrupting content is in the form of quantitative data (e.g., numbers), the interruptee usually has to divert attention away from the primary task immediately to memorize the information or use a memory tool (e.g., pen and paper) for support. For example (18): *A nursing assistant uses Vocera to report the blood sugar levels of a patient to a nurse. The nurse is currently collecting medication from the Medication Supply Cabinet. The nurse cannot remember the numbers using her memory, so she must stop what she is doing to write down the blood sugar level using a piece of paper.*

3.6 Discussion

This research was an observational study conducted in a hospital's acute care units. Using a STS approach, we captured the distinguishing characteristics of HCD-mediated interruptions dynamics as compared to face-to-face interruptions. These findings reflect how the integration of HCD affects interruption dynamics and therefore nursing work performance from various perspectives. The following discussion is focused on the interpretation of the examples presented in the Result.

Facilitators

HCD facilitates nurses' workflow continuity. Results (example 9) showed that following a simple procedure, using HCDs, nurses can communicate information with another healthcare provider within the work system who is not physically present while continuing their current workflow. With HCD, in many situations, nurses are able to relay and receive an important message staying in one location, as shown in example 17. Also,

they can delay or decline an interruption that occurs at an inappropriate time. Therefore, in most situations, workflow can stay intact. This result is consistent with previous research, which finds that HCD can improve staff communication, allow more work flexibility, and free up nursing time (Pemmasani et al., 2014; Richardson & Ash, 2010).

HCD also facilitates the efficiency of nursing communication. Comparing example 6 with 8, with the HCD, interrupters may find the right person more conveniently and rapidly to achieve a goal, either to get an answer or to disseminate a message, at one location. The reduced travel and movement allows nurses to spend more time with their patients, reducing the time pressure surrounding direct patient care activities. Research has shown that the amount of time spent in clinical work can be associated with better patient outcomes and greater nurse satisfaction (Duffield et al., 2011; Miller, Deets, & Miller, 1997). Also time-saving is important to improve nursing work quality and wellness, since research has shown that time pressure is a major source of nurses' stress (Yang, Rivera, & Van Aken, 2014).

HCD also adds flexibility nurses feel they have in responding to interruptions. Results (16) show that interruptees appear more comfortable declining or delaying an interruption via HCD than face-to-face. Perhaps declining or delaying an interruption via HCD is easier or perceived to be less rude as the two sides do not see each other at the time of the interruption. The interruptee delays or declines calls using the HCD based on an assessment of their own interruptibility without a judgment of the interrupter's urgency. With the added flexibility, interruptees can determine the best time for themselves to attend to the interrupting task. In comparison, for face-to-face interruptions,

the interruptee makes an assessment based on their own interruptibility as well as the interrupter and interrupting task (Rivera, 2014). Perhaps the assessment makes nurses aware of the urgency of the interrupting task and more likely to respond to them immediately, as shown in example 15, even at the cost of disrupting their own workflow.

Barriers

The first barrier of HCD-mediated interruption is related to its interrupter-oriented nature. That said, due to the geographical dispersion between the interrupter and interruptee, the initiation of an interruption depends mainly on the interrupter's needs, while ignoring the interruptee's interruptibility. Therefore, this lack of assessment from the interruptee's perspective can sometimes result in unsuccessful communication (as shown in example 5), or communication risking workflow disruptiveness (as shown in example 18). Rivera-Rodriguez and Karsh (2010) described the complexity and simultaneous implications of both sides during interruptions as the interrupter-interruptee paradigm. Using this paradigm (Rivera-Rodriguez & Karsh, 2010) to interpret HCD-mediated interruptions, considering example 4, the interrupter may gain significantly from an interruption when receiving information and getting answers to questions using HCD. However, because of the lack of SA regarding the interruptee's primary tasks and interruptiblity, it is less likely for an interruptee to gain from the interruption at an appropriate time. Interruptions may be more likely beneficial to the interruptees through face-to-face, such as receiving a time-sensitive piece of information at an appropriate time, as shown in example 2.

The second barrier of HCD-mediated interruptions is related to the interruptee's overprotection of their workflow. Overprotecting workflow from HCD-mediated interruptions occurs in several manners, as shown in example 16. First, the interruptee may decline the interruption prior to knowing that the content may be important/urgent or useful to their own workflow. Second, interruptee's may decline the call even if it is at an appropriate time because they do not feel the pressure to accept the interruption as they do with face-to-face interruptions and prefer to keep their workflow intact. Therefore, it becomes a barrier when necessary information must be communicated to the interruptee, but are declined by the interruptee when it really should not be. Based on the examples found in a previous face-to-face interruption study (Rivera, 2014), it is possible that although the interruptee's workflow is disrupted, they may actually gain from the content being delivered via the interruption. However, because it is much easier to decline a HCD-mediated interruption than a face-to-face interruption, the interruptee may decline thinking they are preserving their workflow, but in fact missing out on the benefits related to the interruption content. In cases where the information must reach the interruptee, the interrupter has to use other methods to deliver that content.

The third barrier of HCD-mediated interruptions is related to the delay or slowness of the content delivery when using HCD. There are many reasons for this. Firstly, unlike face-to-face interruptions, using Vocera introduces lags and difficulties when the interrupter connects to the interruptee, as shown in example 10. Secondly, without the affective cues embedded in the face-to-face interruptions, as shown in example 7, the interruptee cannot anticipate the interruption content, which may be

important in creating a mental model of the situation which would help support their response to the interruption. HCD delays this process until after the message is fully delivered, which further delays the interruptee's response. Thirdly, it is the nature that through signal processing, the sound becomes more monotone and can lack clarity. It takes additional time to confirm and rephrase the real meaning of the interruption. Due to the delay in content delivery, perhaps certain types of information are not suitable to be delivered using HCD, such as time-sensitive medication updates, important changes, and real time updates.

The last barrier of HCD-mediated interruptions is related to the inaccuracy of the message when delivered via HCD. Contextual factors and environmental interference compounded with technological issues affect the performance of Vocera, resulting in the inaccuracy or inefficiency of information communicated, as shown in examples 11-15. This finding indicates the importance to investigate HCD usability in the real world, where the contextual factors, such as patient privacy, workflow complexity, individual differences and environmental noises related to product performance, are situated (Karsh, 2004).

Recommendations

Using a STS approach, it is not only to improve HCDs, but also to optimize both the social and technical subsystems (Kleiner, 2008), so that interventions are compatible with work system environment and patient care workflow (Karsh, Holden, Alper, & Or, 2006). Therefore, based on the identified barriers, we proposed preliminary

recommendations for the adaptation and compatibility of HCDs with the work system, environment and workflow, using a multi-layer lens framework (Karsh, 2006).

Firstly, technological solutions can be integrated to help increase the interrupter's SA of the interruptee's interruptibility to reduce the frequency of ill-timed interruptions. For example, radio-frequency identification (RFID) location function can be integrated with Vocera to provide the interruptee's approximate location to the interrupter. Because location can infer the type of task that is being performed (e.g., patient room implies direct patient care activities), the interrupter can then use that information to make a decision of whether to interrupt or not (Rivera, 2014). To further enhance this solution, a mobile app may be developed, which can be connected with Vocera to generate a real-time video-based image showing the primary task of the intended interruptee.

Beyond technology advancements, nurses can be educated and trained to understand the effects of interruptions, when to appropriately interrupt and via which means: face-to-face vs. HCD-mediated. We have shown that both methods have their pros and cons. While face-to-face interruptions contain affective cues and increased clarity, HCD-mediated interruptions tend to be more convenient and timesaving for certain type of information. With the training, nurses will understand how to initiate and manage different types of interruptions using different methods, to benefits both sides of the interruption. This recommendation is in supplement to training of interrupting-handling strategies, which suggest that clinical staff should be trained to deal with interruptions using a sense of control depending on the situation and perceived effects of task performance, such as immediate attendance, multitask, or delay (Li et al., 2011).

Thirdly, prior to and after implementing HCD, a systematic Work System Analysis (WSA) (Karsh & Alper, 2005) is needed to uncover the specific contextual factors that may negatively impact the product's performance (e.g., wireless dead-spots, noisy environments). Different work systems exhibit unique characteristics. With a WSA, it helps to proactively identify potential barriers so that they can be mitigated prior to a full implementation of new technologies/devices that are not compatible with other elements within the work system (Karsh & Alper, 2005).

Lastly, we must urge policy makers to mandate human factors principles and evaluation methodologies into the novel medical device design and implementation process. Healthcare lags behind many other industries (e.g., nuclear, aviation, and transportation) that actually require human factors principles be applied in the design phase followed by rigorous testing of products prior to implementation (Institute of Medicine, 2000). While the Food and Drug Administration requires usability testing of medical devices, the scope is quite narrow, as the guidelines are primarily only concerned with device safety and effectiveness (Story, 2012). Through a wider scope and a systems perspective, such as applying human factors to optimize the compatibility of novel technologies with other components in the work system, healthcare organizations, employees, and patients can benefit more from safer, more integrated systems.

Limitations

This study had several limitations. First, it was conducted at one hospital. Therefore, some of the findings, especially the identified contextual factors that impact the performance of Vocera, may not be generalizable to other healthcare settings. Second,

one single observer collected the data. This fact may affect the collection of data because it is only from one perspective. However, thirty hours observation may overcome this limitation and having one observer increases standardization and consistency of the data. In this study, our objective was to explore, understand, and differentiate HCD-mediated interruption dynamics and their effects as an initial step, with more to follow.

3.7 Conclusion

In this study, we took a STS approach to understand HCD-mediated interruptions within the real nursing work environment. We identified three overarching themes: assessment prior to interrupting, interruption content delivery, and response to interruptions. The themes and the observation events under each theme reflected the unique role of HCD in affecting interruption dynamics and nursing work. Building upon the understanding, we proposed system design recommendations, organizational-level interventions, and policy suggestions to facilitate the successful integration of HCDs in the hospital settings in the future.

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CHAPTER 4: HCD-MEDIATED INTERRUPTIONS: UNDERSTANDING THE SYSTEM FACTORS

The chapter presents a manuscript to be submitted to Applied Ergonomics. It is an extension of the preliminary research of HCD-mediated interruptions in nursing work (Yang & Rivera, 2015). Specifically, the objective of this chapter is to understand system factors in HCD interruption dynamics and their influences on nurses' decisions and performance regarding the use of HCD for interruptions in Pediatric Intensive Care Units (PICUs). The Method and Result sections are lengthier than the requirements of the journal, to offer detailed explanations for this dissertation. They will be modified accordingly for submission.

4.1 Introduction

Interruptions are events that request attention, causing a person to cease their current task for a period of time (Sanderson & Grundgeiger, 2015). Interruptions occur frequently in healthcare work systems, and have been associated with potential adverse events, procedural failures, and clinical or medical errors (Alvarez & Coiera, 2006; Flynn et al., 1999; Institute of Medicine, 2000; Westbrook, Woods, Rob, Dunsmuir, & Day, 2010; Wiegmann, ElBardissi, Dearani, Daly, & Sundt, 2007). Interruptions have been mostly studied as isolated events from the interruptee's perspective (Rivera-Rodriguez & Karsh, 2010; Westbrook, 2014). However, from a sociotechnical systems perspective, interruptions represent the processes through which interrupters and interruptees interact with one another (Rivera, 2014; Werner & Holden, 2015). The process starts when the interrupter initiates the interruption, continues as the interruption content is

communicated, and finally progresses to the interruptee managing the interruption (Yang & Rivera, 2015). Throughout the process, interruptions are shaped by system factors within the interruption dynamics (Werner & Holden, 2015). System factors identified in the current research include the interruption's position, importance, urgency, frequency, flow and modality (Karsh, Weinger, Abbott, & Wears, 2010; Li, Magrabi, & Coiera, 2012; Rivera-Rodriguez & Karsh, 2010; Rivera, 2014; Walter, Li, Dunsmuir, & Westbrook, 2013). They influence both interrupter's and interruptee's decisions and performance (Rivera, 2014).

However, the identified system factors are mostly related to the characteristics and content of the interruptions. In addition to the characteristics and content of an interruption, the context of an interruption should also be considered (Sasangohar, Donmez, Easty, Storey, & Trbovich, 2014). System factors are distributed throughout the sociotechnical work system, related to several interacting components: the individual and team characteristics, the human-system interface, the nature of work, the physical work environment, the organizational culture and infrastructure, and the external environment (Carayon et al., 2006; Holden et al., 2013). The interacting components are connected by causal paths and mechanisms to produce work processes and outcomes (Harr & Kaptelinin, 2012; Holden et al., 2013). In other words, individual and team decisions and performance are not just based on the internal perceptions, consciousness, and experience of an interruption itself (Moustakas, 1994); they might be complicated by a specific context, interweaving the effects of physical activities, mental awareness, rituals, and social interactions (Harrison, Tatar, & Sengers, 2007).

Moreover, the identified system factors are mostly based on the face-to-face interruption dynamics. However, synchronous communication device, such as Hands-free Communication Devices (HCDs), also contribute to interruptions in the nursing work system (Parker & Coiera, 2000). The current research of HCDs has limited scope, with focuses on the interruption frequency, user satisfaction, communication quality, reliability, and the potential to improve nursing work efficiency (Breslin, Greskovich, & Turisco, 2004; Ernst, Weiss, & Reitsema, 2013; Kuruzovich, Angst, Faraj, & Agarwal, 2008; Pemmasani, Paget, van Woerden, Minamareddy, & Pemmasani, 2014; Vandenkerkhof, Hall, Wilson, Gay, & Duhn, 2009). As a newly added component in the healthcare system, the implementation of HCDs might bring unintended consequences and system failures due to the dramatic changes of interruption dynamics (Yang & Rivera, 2015). The uniqueness of HCD interruption dynamics has not been sufficiently investigated.

The goals of this study are to identify which system factors impact HCD interruption dynamics and to discover how they influence nurses' decisions and performance regarding the use of HCDs. This understanding may uncover the root causes of incompatibilities between HCDs and other components in the sociotechnical system, and ultimately have the potential to improve the resilience of healthcare work systems and patient safety. Depicting the results using a descriptive model of HCD interruption dynamics, two specific Research Questions (RQs) of this study are answered:

RQ 1: Which system factors impact HCD interruption dynamics?

RQ 2: How do system factors in HCD interruption dynamics influence nurses' decisions and performance regarding the use of HCDs?

Theoretical Frameworks

Two specific theoretical frameworks were selected to guide this research: the meso-ergonomics paradigm and activity theory. In this study, the meso-ergonomics paradigm was primarily used for contextual inquiry, and activity theory was primarily used as a basis for the descriptive model.

Meso-ergnomics is defined as "an open systems approach to the development of macroergonomic theory and research whereby the relationship between variables in at least two different levels or echelons are studied, and one of the variables is a macroergonomic outcome of interest such as performance, stress, injury, technology acceptance, or quality of worklife" (Karsh, 2006; page 2). In this definition, "level" means the unit of measurement, analysis, or inference, such as the individual, group, or organization (Karsh, 2006). The concept of "meso" originates from organizational behavior research, which integrates micro and macro organizational behavior (House, Rousseau, & Thomashunt, 1995). Traditionally, ergonomics is at either the micro (human-computer interface) or macro (human-organization interface) level (Rivera-Rodriguez et al., 2013). The meso-ergonomics paradigm integrates the individual, group, and organizational levels, and allows for the exploration of causal contributions of variables distributed at different levels (Rousseau, 1985; Karsh, Waterson, & Holden, 2014). For example, using a meso-ergonomics paradigm, many barriers and enablers

across levels to the adoption of Electronic Medical Records (EMR) have been identified (Waterson, Eason, & Karsh, 2009).

Therefore, the meso-ergonomics paradigm is especially useful for the development of the observation template and interview protocols for the contextual inquiry. This multi-level and cross-level approach can guide the identification of system factors related to all of the interacting components in the sociotechnical system. In other words, the meso-ergonomic paradigm not only supports the discovery of individual system factors distributed at each level, but also their interactions across levels.

Activity theory "transcends the dichotomies of micro- and macro-, internal and external, mental and social, cognitive and phenomenological, observation and intervention, in analysis and redesign of work" (Engeström, 2000; page 960). It is a framework that is useful to understand a complex system and analyze a phenomenon (Engeström, 2000). It distinguishes itself from other cognitive theories by incorporating social and cultural context into cognition (Halverson, 2002). The theoretical foundation of activity theory is rooted in the sociocultural and psychology traditions (Vygotsky & Cole, 1978), and has been introduced to the field of Human-Computer Interaction (HCI) (Nardi, 1996) within the post-cognitivist paradigm (Harrison et al., 2007). It reflects the phenomenological nature of human activity (Harrison et al., 2007). In activity theory, human activity is the central unit of analysis, and it is defined as a goal-directed interaction between a subject and an object through the use of a mediating tool, in a physical environment, with cultural influences and social standings, to make an influence on decisions and performance (Engeström, 1993). All of these aspects are connected to

influence the outcome, and disturbances might occur when these components interact (Engeström, 2000).

Therefore, activity theory is useful for the development of the descriptive model showing the HCD interruption dynamics in this study. Using activity theory, the entire process of HCD-mediated interruptions can be described as an interrupter (Subject) interacts with an interruptee (Object) through a HCD (Mediating tool), and their decisions and performance are subject to the context, such as Culture/Policy (Rules), Work Environment (Community), and Teamwork (Division of Labor). Also, dynamic processes (Disturbance) might occur when these components are interacted. Using activity theory to depict HCD interruption dynamics can provide a holistic understanding of the interruption process. Also, it provides the basis to display the causal paths and mechanisms of system factors in HCD interruption dynamics that influence nurses' decisions and performance when using such devices.

4.2 Methods

All procedures in this study were approved by the Institutional Review Board (IRB) in the hospital conducting this research. The Institutional Review Board of Clemson University reviewed all the documents and deferred authorization to the hospital.

Through a pragmatic lens, research methods were chosen based on the goals (Creswell, 2012). As this is a study of an unexplored phenomenon, we selected qualitative methods as this is an inductive approach (Gray, 2004). They can provide a

comprehensive understanding of a phenomenon with rich contextual information (Curry, Nembhard, & Bradley, 2009; Glaser & Strauss, 1999).

The nature of qualitative research is different from quantitative research in several ways: 1) interview data is collected as filtered by the participant's mind; therefore, the data is actually the interviewee's "perception of reality" (Ajzen, 1991), rather than the "reality"; 2) observers or interviewers themselves act as the "human instrument" for the data collection (Creswell, 2012) with their own ontological and epistemological assumptions (Guba & Lincoln, 1994), rather than the "true" measures; and 3) qualitative research aims to reach data saturation to describe and interpret a phenomenon in naturalistic context, rather than sufficient power for causal relationships and generalization of findings (Bowen, 2008). In sum, qualitative research is interested in how a phenomenon in the world is understood and sensed by people, and how the meanings and implications are interpreted by the researcher. The result of qualitative research can open up new perspectives for developing hypotheses or theories, which can be tested in the future using other research design methods (Vasilachis de Gialdino, 2009).

Study Setting

The research was conducted in Pediatric Intensive Care Units (PICUs) in a children's hospital located in the Midwestern United States. The hospital is a 306-bed research-teaching, not-for-profit, and freestanding medical facility that provides inpatient and outpatient, secondary, tertiary, and quaternary medical care and services. Most patients admitted to this hospital are younger than 19 years old. Each nurse in these two

units was equipped with a HCD, specifically Vocera. To the best of our knowledge, Vocera Communication, Inc. is currently the only company manufacturing HCDs in the domain of healthcare (Richardson & Ash, 2010); therefore, for the remainder of this paper we will refer to HCDs by the brand name "Vocera".

PICUs were selected as the study site based on the following reasons: 1) Young children are considered, by the Agency for Healthcare Research and Quality (AHRQ), to be a vulnerable patient population that should be studied by human factors and patient safety researchers; 2) Nurses in ICUs work in fast-paced environments that include multiple nursing communications and handoffs (Newcomb, 2011), in which they initiate and incur interruptions frequently (Alvarez & Coiera, 2005), and are therefore affected by interruptions (Gupta et al., 2013).

We purposefully sampled nurses from two different PICUs of the same size (24-beds): one was a surgical unit primarily for cardiac patients, and the other was a general medical unit on another floor. Although the results of qualitative research are contextually sensitive (Henwood & Pidgeon, 1992) and the purpose of qualitative research is not to generalize results to other work systems (Creswell, 2012), sampling participants from two sub-systems may enhance the diversification and, therefore, the potential for transferability of the results (Gibbs et al., 2007).

Participants

Registered Nurses (RN) working in two PICUs made up the population from which participants for this study were sampled. Nurses are at the "sharp end" of patient care (Hughes, 2008); they have the most frequent contact with patients and are

considered the last line of defense against medical errors (Henriksen, Dayton, Keyes, Carayon, & Hughes, 2008; Liaw, Scherpbier, Klainin-Yobas, & Rethans, 2011). Therefore, framing the interruption study within the nursing work system created abundant potential to improve patient safety (Ebright, 2010). From a systems perspective, nurse participants represented both sides of the interruption: they may either be an interrupter using Vocera to interrupt other personnel, or an interruptee receiving a Vocera call initiated by other personnel. Nurse participants included both charge nurses and staff nurses working any work shifts (day and night). Other personnel may include other nurses, physicians, ancillary staff, respiratory therapists, Health Unit Coordinators (HUCs), care partners, etc.

Recruitment

After obtaining the IRB approvals, we met with the nurse manager of the PICUs to discuss plans for the study. We introduced the study to the unit managers and charge nurses first, and then potential RN participants during the daily staff meeting. Posters were placed around the units, with the research objectives and a researcher's picture on each of them. Using these methods, nurses were able to get a general awareness of the study and develop a relationship with the researcher before the research. The informed consent process may become easier (Corrigan, 2003), because many questions and concerns regarding the objectives of this study might have already been addressed.

There were two phases for this research. The first phase was observations. A human factors researcher (YY) did 5-hour pilot observations in the PICUs accompanied by a nurse manager (KM) and another human factors researcher (AJR) working in the

hospital, to become familiar with the nursing work system and PICU environments. Formal observations were then conducted by one human factors researcher (YY). Convenience sampling was used to select the nurse participants, depending on the observation time and the nurses working in the units during that time (Creswell, 2012). The participants were scheduled one day ahead of observation with the assistance of the nurse manager on a voluntary basis. At the beginning of each observation, bearing minimum intrusion in mind, we provided the participant with an information sheet followed by a brief and general introduction of what the observation would entail. Participants gave their verbal consent to participate and then the observation began.

The second phase was in-depth semi-structured interviews. To comply with the regulatory requirements regarding nurses' work schedules in PICU, we developed a relief nurse model: to have a relief nurse cover a 4-hour interview session. Three to four semi-structured interviews were conducted in each session by one to two human factors engineers (YY and AJR). Convenience sampling was used to select nurses for interview, depending on the interview session time and the nurses working in the units during that time (Creswell, 2012). At the beginning of each interview, we provided the participant with an information sheet followed by a brief and general introduction of what the interview would entail. Participants gave their verbal consent to participate, with audio recording, and then the interview began.

Data Collection

The purposes of the observations were to obtain necessary domain knowledge and prepare the interview protocol and probing questions. Observations focused on

interruption events mediated by Vocera and the nurses' decisions and performance when using such device. An observation template (See Appendix A) was created based on the different levels in the meso-ergonomics paradigm: user experience (UX), cognition, team, and organization (Karsh, 2006). The template provided space to record interruption times and descriptions, as well as the contextual information related to the interruption events at the four levels.

To observe the nurse participant, the observer stood inside the patient room, or the anteroom if the patient was in isolation. The observer followed the nurse if they went out of the room to pick up supplies, send a blood sample to the lab, chart the patient's data in the computer, help other nurses, or engage in a conversation. Little conversation occurred during the observations between observer and participant, unless the nurse proactively talked to the observer, or the observer determined a time when the nurse was free to talk. Observation data were recorded by hand, using a pen and notebook. Reflective notes and comments based on observation data and conversations were made after each observation along with the observation data (Devers, 1999). At the end of each observation day, data was transcribed into typed notes and saved them on a laptop with password protection. A total of five RNs were shadowed, with each observation period lasting roughly 3 hours. The observation data reached saturation after a total of 15 hours.

In-depth interviews were conducted with PICU nurses as the second phase of this study. Human decisions and performance may not always be observable and obvious (Austin & Delaney, 1998), therefore, the purpose of the interviews was to understand system factors within the interruption dynamics and their influences on nurses' decisions

and performance regarding the use of Vocera for the interruption at a deeper level. An interview protocol was created based on the four different levels of the meso-ergonomics paradigm. Probe questions were created to link those levels. We also created scenarios based on the observation data to facilitate the explanation of interview questions. The interview started with a general question: "How do you use Vocera in a typical day?" And questions at each level were asked followed by the probes based on the answers. Participants were asked to fill out a post-interview demographic survey at the end of interviews. The interview protocol is shown in Appendix B. Demographics of the interview participants are shown in the Table 4.1. The participants were sampled from two different PICUs varied in their roles, age, and experience. While some of them used HCDs in life, such as the blue-tooth in the car, no other HCDs other than Vocera were used during their work. This further validates that Vocera is currently the only brand of HCDs used in the healthcare settings.

Interviews occurred in an office inside the PICUs and were audio recorded by two recorders. These audio recordings were sent to a professional transcriptionist, who transcribed the recordings verbatim (Padgett, 2008). Upon receiving the transcriptions, we checked the accuracy of each transcription and removed all identifiable information. A total of 15 RNs participated in the interviews, with each interview lasting 25 to 40 minutes. The number of participants exceeded the recommended number of 12 for sufficient reliability (Guest, Bunce, & Johnson, 2006). Among the 15 interviewees, six of them had two interviewers: YY led with the interview questions, and AJR assisted with probing. The other nine interviews were led by one interviewer (YY).

Table 4.1: Demographics of Interview Participants

Unit	Surgical cardiac ICU: n=9 (60%) Medical general ICU: n=6 (40%)
Role	Nurse with Rapid Response Team (RRT) roles:n= 2 (13%) Staff RNs working in the PICU: n= 11(73%) Others (charge nurse or travel nurse): n=2 (13%)
Age	18-34: n=8 (53%) 35-44: n=4 (27%) 45-64: n=3 (20%)
Time worked in this hospital	Range: 8 months-19 years
Time as a nurse	Range: 8 months-35 years
Time using HCDs during work	Range: 8 months-10 years
Expriences in using HCDs in life	Yes: n=7 (47%) No: n=8 (53%)
Other HCDs besides Vocera for nursing work	Yes: n=0 (0) No: n=15 (100%)

Data Analysis

We firstly analyzed the observation data. After reviewing the typed notes of each interruption event, scenarios were created to reflect representative interruption events during the observation. Scenarios described the use of Vocera from the perspective of their users (Rosson & Carroll, 2001). As stated previously, during observations, participants acted as the role of the interrupter when they initiated the Vocera interruption, and the role of interruptee when they received a Vocera call interrupting them. This allowed us to provide real-life examples to participants during the interviews that covered the complete HCD-mediated interruption dynamics.

Observation events, with details of the contextual information and the nurses' decisions and performance, were deductively coded into a matrix (Table 4.2). The coding of an event was determined by the following criteria: Was the interruption initiated by an interrupter or managed by an interruptee? And was the nurse's decision made before or after the call was connected? For example, if a nurse was observed initiating Vocera to call, that event was coded as A1. If a nurse was observed rejecting an incoming Vocera call, that event was coded as A2. If a nurse was observed terminating a call after being told the interruptee is busy, that event was coded as B1. If a nurse receiving a Vocera call was observed telling the caller that they are currently busy, that event was coded as B2. This categorization provided a clear picture of the decisions made and by whom (interrupter vs. interruptee) while using Vocera. All the events coded in this matrix were observable interruption events.

Table 4.2: Matrix for the Observation Data

	A. Prior to connection of Vocera call	B. After Vocera is connected
1. Interrupter	**A1**	**B1**
2. Interruptee	**A2**	**B2**

Before the formal interview data analysis, the transcriptions were read several times to have a general understanding and familiarity with the entire dataset. The formal coding of the interview data was followed by the Three Iteration method (Anfara, Brown, & Mangione, 2002). In the first iteration, the data was coded using an inductive method using the comment function of Microsoft Word. Every sentence in the transcription was

read and the chunks of data that represented patterns related to the research questions were labeled using descriptive codes (Saldana, 2009). All the descriptive codes were put together.

The second iteration of coding was conducted in NVivo 10© (QSR International Pty Ltd., Melbourne Australia). In the second iteration, each descriptive code was reviewed and compared using the constant comparative analysis method (Glaser & Strauss, 1999). A hierarchical coding structure was developed based on the relationship of the descriptive codes. The codes were integrated as themes, and the themes were moved up and down as overarching themes and sub-themes. Descriptive codes that did not reflect any patterns of the phenomenon were removed from the coding structure. After coding chucks of data into the themes, the coding file was sent the NVivo 10© file to another researcher (AJR) for a skeptical review (Devers, 1999). Discrepancies were discussed, appropriate changes regarding the coding structure and themes were made, and chunks of data within each theme were restructured. Overarching themes and sub-themes that were directly related to the research questions in this study were put together. Others that were not directly related to the research questions were set aside. The final thematic structure reflected a number of system factors in HCD interruption dynamics.

In the third iteration, the dataset was applied to descriptive model development (Anfara et al., 2002). A descriptive model of Vocera interruption dynamics was created, with the components of Interrupter, Interruptee, Vocera, Culture/Policy, Work Environment, and Teamwork, corresponding to the components in the activity theory respectively: Subject, Object, Mediating Tool, Rules, Community and Division of Labor.

An additional component, Interruption, was added to the descriptive model. Themes related to system factors were categorized into a component or a dynamic process of components in the descriptive model.

Strategies to Ensure Research Rigor

We used the following methods to ensure research rigor, including credibility, transferability, dependability, and confirmability (Anfara et al., 2002) (See Table 4.3). Specifically, the strategies included research method triangulation of both observations and interviews (Creswell, 2013) and expert member checks (Devers, 1999) for credibility; purposeful sampling from the two units (Gibbs et al., 2007) for transferability; structured observation templates (Neuman, 2000), semi-structured interview protocols, and an audit trail of the decisions related to the analysis methodologies, progress, and adjustments and reconstructions of codes and themes (Rodgers & Cowles, 1993; Morse, Barrett, Mayan, Olson, & Spiers, 2008) for dependability; and self-reflections throughout the process (Devers, 1999), as well as multiple rounds of the coding (Anfara et al., 2002) for confirmability. Additionally, the primary coder (YY) has experience in conducting observations and interviews during his graduate studies, further ensuring research rigor (Patton, 1999).

Table 4.3: Strategies to Ensure Research Rigors

Credibility	Triangulation (Creswell, 2013); Expert member check (Devers, 1999); Researcher's expereince in qualitative research (Patton, 1999)
Transferability	Purposeful sampling from two units (Gibbs et al., 2007)
Dependability	Structured qualitative research tools (Neuman, 2000); Audit trail (Rodgers & Cowles, 1993; Morse et al., 2008)
Confirmability	Self-reflections throughout the process (Devers, 1999); multiple rounds of coding (Anfara et al., 2002)

4.3 Results

Nurses' decisions and performance regarding the use of Vocera

Prior to presenting the main results of this study (e.g., RQs 1-2), it is necessary to highlight nurses' decisions and performance regarding the use of Vocera for interruptions (See Figure 4.1). Although this section primarily presents results of observations, Figure 4.1 combined the results of observations and interviews.

Fourteen Vocera interruption events were observed during the 15 hour observation, each with contextual information. Observation events were categorized into the quadrant of the matrix showing the decisions made by nurses regarding the use of Vocera for interruptions (See Appendix C).

Before a Vocera call is accepted, when there is a need for interruption, the interrupter makes the decision of whether to initiate the Vocera call immediately, delay it, or use another method of communication. The interruptee, upon receiving the Vocera call, makes the decision of how to manage the call, (i.e., to accept, reject, or ignore the call).

If the Vocera call is accepted, after being connected, the interrupter makes the decision of how to proceed with the conversation. They may start to talk to the interruptee about the interruption content, or terminate the Vocera call. At the same time, the interruptee makes the decision of how to respond to the caller. They may immediately answer questions and provide help, step out of the patient room and start a conversation, or terminate the Vocera call.

The use of Vocera can influence the nurses' work performance. The influence can be positive because Vocera can quickly connect a call and support a conversation. For example, we observed an event like this: *A charge nurse was working on the night shift assignment. She received a Vocera call from a charge nurse of the other unit. They talk about floating nurses to this unit.* In this example, Vocera saved the nurse's time and allowed for effective communication.

The use of Vocera may also negatively influence nurses' workflow, workload and quality of patient care nurses provide. For example, we observed an event like this: *After a patient was admitted, a nurse was working on setting up the Intravenous (IV) infusion pump. She received a Vocera call from the HUC. She stopped setting up the pump and accepted the call. The call was from the patient's parents, calling about visiting. The nurse told HUC that the parents need to wait for several minutes; then she finished the call and resumed what she was doing.* In this event, accepting a Vocera call required attention, disrupting her primary workflow, thus negatively impacting the quality of patient care. A similar event is like this: *When the nurse was cleaning the patient's mouth in isolation room, he received a Vocera call. He stopped the task, reversed his position,*

and used the only one free hand to move Vocera towards himself (the other hand was to hold the tube of the mouth cleaning equipment). The call was from HUC about blood ready from the blood bank and its expiration. In this event, the primary task was disrupted and added additional workflow within a short period of time. The nurse had limited capability to manage the call because his hands were occupied, resulting in the potential for an error of the direct patient care.

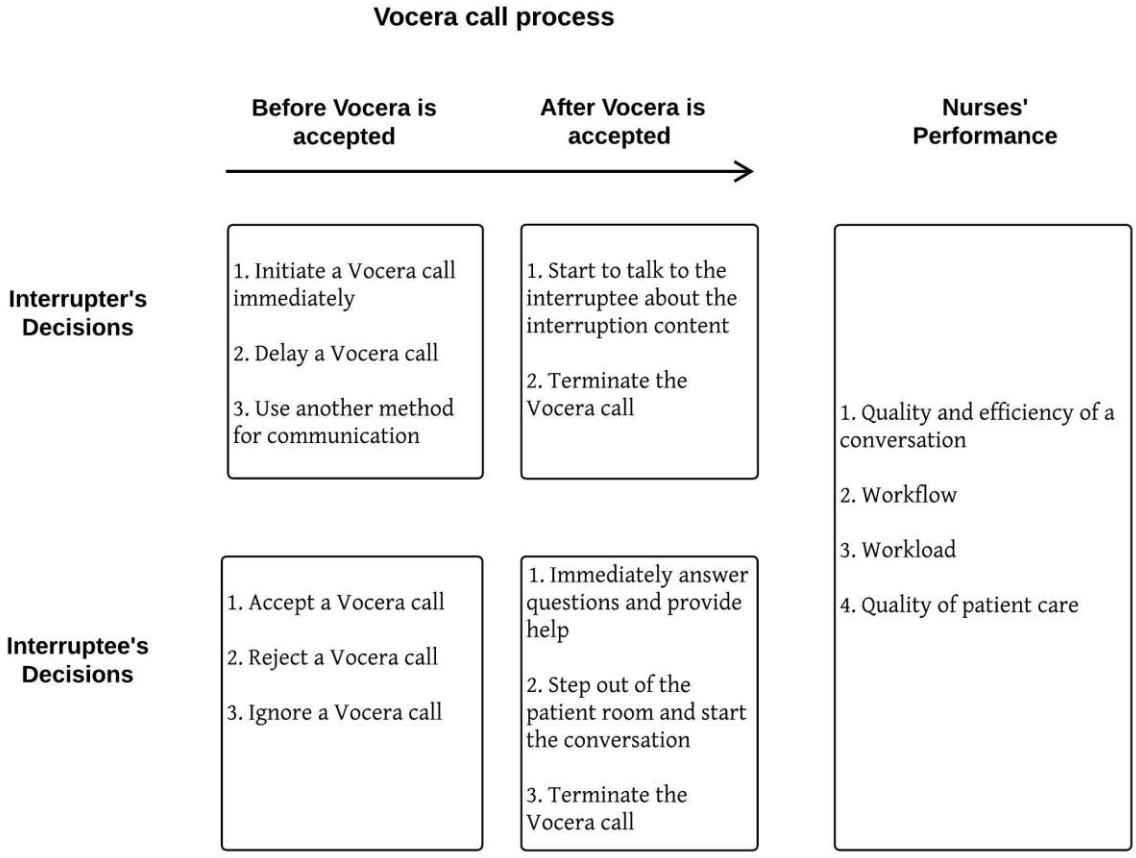

Figure 4.1: Nurses' decisions and performance regarding the use of Vocera

Which system factors impact HCD interruption dynamics (**RQ 1**)?

The list of system factors is shown in Table 4.4. Five proximal system factors, 17 indicator or moderator system factors, and four distal system factors were identified based on the analysis of interview data. Proximal system factors are distinguished by their immediate impact on interruption dynamics, while the impact of distal system factors may be further down the causal chain and emerge related to specific situations (Holden et al., 2013; Karsh, Holden, Alper, & Or, 2006). Both indicator and moderator system factors shape the context; the indicator system factors are composed of previous knowledge of the system that acts as partial input to the proximal system factors, and the moderator system factors are contextual circumstances that influence the proximal system factors.

Table 4.4: The List of System Factors

No.	System factors	Description	Relation to the descriptive model
Proximal system factors			
1	The nature of the interruption	Interrupter's perception of the need for an interruption	Dynamic process of Interrupter and Interruption
2	Perceived availability of interruptee	Interrupter's perception of interruptee's availability	Dynamic process of Interrupter and Interruptee
3	The perceived importance of interruption content	Interruptee's perception of the importance of an interruption	Dynamic process of Interruptee and Interruption
4	The interruptee's availability	Interruptee's availability at the time of receiving a Vocera call	Component of Interruptee
5	Vocera user experience (UX)	UX of Vocera	Dynamic processes of interrupter and Vocera, as well as interruptee and Vocera
Indicator or Moderator system factors			
2A	The interruptee's schedule	Work routine of the units	Component of Culture/Policy
2B	The role of the interruptee	Interruptee's work role within the PICU team	Component of Teamwork

2C	The environmental cue	Cues embedded in the work environment that suggest the interruptee's availability	Component of Work Environment
3A	An expected Vocera call	Interruptee's expectation for an interruption from Vocera	Component of Interruptee
3B	The role of the interrupter	Interrupter's work role within the PICU team	Component of Teamwork
3C	The interruptee's nursing role	Interruptee's work role within the nursing team	Component of Teamwork
3D	Caller's information communicated by Vocera	Vocera's communication of the interrupter's identifiable information	Component of Vocera
4A	Direct patient care	Suction, wound dressing change, medication administration, sterile procedures, etc	Component of Interruptee
4B	Meeting	Team-based bedside rounds and patient admission team briefings	Component of Interruptee
4C	Emergency or code situation	When a patient's condition deteriorates and requires intense nursing and/or healthcare team intervention.	Component of Interruptee
4D	Conversations with family	Conversations between nurses and patients for educational and consoling purposes	Component of Interruptee
5A	Battery	Vocera's battery draining (and battery indicator)	Component of Vocera
5B	Vocera voice recognition	Performance of Vocera's voice command feature	Component of Vocera
5C	Vocera's signal coverage	Vocera's wireless network inside and outside PICU	Component of Work Environment
5D	Noise	Background noise and patients' noise in PICU work environment	Component of Work Environment
5E	The healthcare protective clothing standards	During sterile procedures in isolation, nurses are required to wear gowns and gloves	Component of Culture/Policy
5F	Familiarity with other team members	The interrupter's knowledge of the names of the other team members in the PICU	Component of Interrupter
Distal System Factors			
6	Patient room comfort	The comfort of PICU environment for patients and families	Component of Work Environment
7	Patient privacy	Compliance with regulations that protect patient's privacy	Component of Culture/Policy
8	Culture of PICU	The way things are done in a particular work system	Component of Culture/Policy
9	Training	Guidance to standardize the use of Vocera's for interruptions	Component of Culture/Policy

How do system factors in HCD interruption dynamics influence nurses' decisions and performance regarding the use of HCDs (**RQ 2**)?

A descriptive model of interruption dynamics has been developed based on the activity theory model (Figure 4.2). Proximal system factors, their indictor or moderator system factors, and distal system factors derived from the thematic structure of the interview coding were depicted in this model in different colors. As shown in the descriptive model, five proximal system factors were found within the four-way interaction of Interrupter-Vocera-Interruption-Interruptee (Refer to top portion of Figure 4.2). That said, proximal system factors do not function alone; they interact with each other to influence the nurses' decisions and performance regarding the use of Vocera for interruptions. Additionally, each proximal system factor may depend on a number of indicator or moderator system factors that are distributed within the system's context. They interact with the proximal system factors to influence nurses' decisions and performance. Moreover, the context-based distal system factors, related to the components of culture/policy and work environment, act distantly on the causal chain to influence nurses' decisions and performance regarding the use of Vocera for interruptions. Distal system factors reside outside the four-way interaction of Interrupter-Vocera-Interruption-Interruptee in the descriptive model of Vocera interruption dynamics. They are related to the components of Culture/Policy, and Work Environment (refer to the bottom portion of Figure 4.2). Compared to proximal system factors, distal system factors are further down the causal chain to influence nurses' decisions and performance.

Nurses' decisions and performance are closely related; therefore, a system factor that influences a decision, might instantly affect the resulting performance. For example, interrupters may initiate an interruption at an interruptee's busy time, thus leading to disruptions in the interruptee's workflow. Also, interruptees may reject a call that is important, impacting the communication efficiency and workflow consistency.

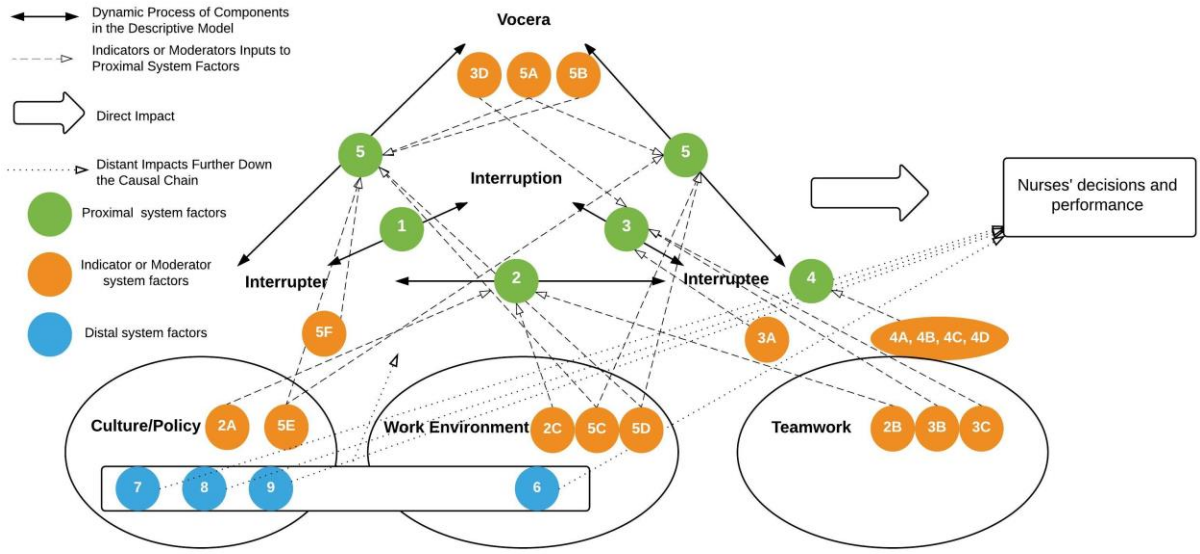

Figure 4.2: The descriptive model of interruption dynamics

In the following section, firstly, we explain each proximal system factor that directly influences the nurses' decisions and performance, and the associated indictor or moderator system factors that provide partial inputs to the proximal factor. Secondly, we explain the interactions of proximal system factors and their influences on nurses' decisions and performance. Lastly, we explain the distal factors distributed in the context that make distant impact further down the causal chain.

Proximal system factors and their associated indicator or moderator system factors

#1: The nature of the interruption

This proximal system factor is related to the dynamic process of Interrupter and Interruption in the descriptive model, i.e., the interrupter's perception of the need for an interruption. If the interruption content is deemed important and time-sensitive, a nurse is likely to initiate an interruption immediately using Vocera. For example, Participant 10 described it like this: "*If there's like an emergent situation, I would just call out of the room [using Vocera] to have someone come help me versus, you know, taking a couple seconds to find someone on the system.*"

#2: Perceived availability of interruptee

This proximal system factor is related to the dynamic process of Interrupter and Interruptee in the descriptive model, i.e., the interrupter's perception of interruptee's availability. If a nurse knows an interruptee is busy, they are unlikely to interrupt another nurse. Participant 3 described it like this: "*There's definitely times where I know somebody else is very busy, so I try not to bother them [during that time]."*

Several indicator system factors help interrupter understand the interruptee's availability, providing them with different degrees of the awareness

#2A: The interruptee's schedule

This indicator system factor is related to the component of Culture/Policy in the descriptive model, i.e., the work routine of the units. Interrupters may know the interruptee's schedule of regular meetings and bedside rounds, which might be the interruptee's busy time. Therefore, interrupters are likely to delay an interruption to a

later time. Participant 1 described it like this: "*And then there's also an hour where [the doctors are] in an afternoon conference, and we don't use the Vocera at all. They're not to be interrupted during that noon conference, from noon to 1:00."*

#2B: The role of the interruptee

This indicator system factor is related to the component of Teamwork in the descriptive model, i.e., interruptee's work role within the PICU team. A particular role can in and of itself dictate one's availability for a Vocera interruption. For example, doctors may attend a lot of meetings and rounds, or be off the floor, during which they are not available for the Vocera call. Therefore, nurses are unlikely to initiate a Vocera call to interrupt doctors. Participant 4 described it like this: "*I know [interruption is] disruptive to [doctors'] huddle, and I'm probably not going to be able to reach them, and they're not going to be able to talk to me anyways."*

#2C: The environmental cue

This moderator system factor is related to the component of Work Environment in the descriptive model, i.e., cues embedded in the work environment that suggest the interruptee's availability. Depending on the location, nurses may receive more or less environmental cues, which can also help them understand other's availability. Most patient rooms in the PICUs do not have views of the doctors' workroom or other patient rooms; therefore, nurses are unlikely know a doctor's status outside their regular meeting time. Due to this, an interrupter's decision regarding a Vocera interruption might be conservative. They are unlikely to initiate an interruption or may instead communicate a

message using a less interruptive method. Participant 6 described it like this: "*I never know like when the doctors are in meetings or whatever, so it's easier just to page them if they're rounding."*

#3: The perceived importance of interruption content

This proximal system factor is related to the dynamic process of Interruptee and Interruption in the descriptive model, i.e., the interruptee's perception of the importance of an interruption. The perceived importance of the interruption content is an important consideration to accept a Vocera call. If a Vocera call is perceived important and urgent, they are likely to accept the call. Participant 13 described it like this: *"I'd need to get a sense of how important [the Vocera interruption is]... Generally, you just have to have a sense of which one is more urgent, finishing what I'm doing, or stopping what I'm doing to [accept the call]."*

Several indictor system factors help interruptees understand the nature of an interruption, with different degrees of the awarness.

#3A: An expected Vocera call

This indicator system factor is related to the component of Interruptee in the descriptive model, i.e. the interruptee's expectation of an interruption from Vocera. An expected Vocera call is generally perceived as important and the interruptee is likely to accept it. An example of an expected Vocera call is when the nurse awaits a notification from someone for upcoming patient care activities. Participant 8 describes it like this*: "I knew that the patient was going to be going for some sort of a procedure. So I knew*

[someone would call me using Vocera to] let me know what time or find out something regarding that procedure, then I would excuse myself from rounds and take the call."

#3B: The role of the caller

This indicator system factor is related to the component of Teamwork in the descriptive model, i.e., the interrupter's work role within the PICU team. When a nurse receives a Vocera call, the caller's name or role is voiced by the Vocera and shown on the Vocera display. A particular role of the caller can indicate the potential content of a Vocera interruption. For example, a call from a nurse with a busy assignment may indicate a need they have related to their patients, which is likely perceived as more important than the interruptee's current task, thus leading them to accept the call. A call from Laboratory may indicate a newly available lab result, which might be perceived as important if it is related to patient care tasks. A call from a doctor may indicate something urgent related to the nurse's patients, which might be perceived as extremely important. A call from a nursing friend at lunchtime may indicate content not related to work, which is less likely to be perceived as important. A call from HUC may indicate an external phone call from the patient's family asking for an update, which is also perceived as relatively less important or urgent depending on the interruptee's current task. Participant 10 described it like this: "*Because if I know it's another nurse, and, you know, they were busy with their, they've been busy with their patients, then it's probably something important. Versus if it's the secretary [HUC], then, you know, it could just be that they're asking, or, you know, like if there's a phone call for me that could be a personal one, it could be for a family."*

Participant 13 described it like this: "*If it's a physician, then I would think that they usually don't call me for, it's pretty important, so I would probably think it's a higher priority."*

Participant 5 described it like this: "*So if my friend is waiting for me to eat lunch or I say, call me and I'll go and we can go eat lunch. If she, you know, calls and then I kind of know what it's about, and I'm in the middle of a conversation, I'll ignore it*."

#3C: The interruptee's nursing role

This indicator system factor is related to the component of Teamwork in the descriptive model, i.e., interruptee's work role within the nursing team. There are different nursing roles in the PICU. The nurse supervisor and manager, super charge nurse, charge nurse, and Rapid Response Team (RRT) nurse are more logistically focused, while the staff nurse's role is at the bedside, more directly interacting with the patient and family. For those nurses with a logistic role, one of their primary job responsibilities is to address questions from bedside nurses in a timely manner. Therefore, every single Vocera call they receive is likely perceived as important, and no call is likely rejected. Participant 14 described it like this: "*Generally, in charge, I don't reject a call too much, because it's usually important."* To the contrary, for staff nurses, their primary responsibility is to care for their assigned patients. Therefore, calls from other nurses might be perceived as less important as they may be related to things like "*changing a diaper or changing bed linens or just have a question about a medication or how to do something at the bedside,"* as Participant 2 described. Additionally, staff nurses feel more comfortable rejecting a Vocera call because they know interrupters may

have other resources to seek help. Participant 1 described it like this: "*It's not perceived as rude or abrupt [for me as a bedside nurse to reject a call]. If [I reject the call, they can] hold down [the main button on Vocera], a sustained hold-down, to do an all-call to the whole unit*." With an all-call to the whole unit, nurses with a logistic role may hear that and come to provide help.

#3D: Caller's information communicated by Vocera

This moderator system factor is related to the component of Vocera in the descriptive model, i.e., Vocera's communication of the interrupter's identifiable information. When receiving a Vocera call, the nurse might hear a correct name or an incorrect name, which may impact their perception of the importance. The information might be inaccurate when a nurse uses a Vocera that another nurse is logged into when his or her own Vocera does not function well. When receiving a Vocera call, the nurse might hear the name of the logged-in nurse, rather than the actual caller. This may lead nurses to make an incorrect assessment regarding the importance of the Vocera call. Participant 8 described it like this: *"if the phone is ringing and our HUC is at lunch or on another call, another nurse might answer the phone, and then they would just Vocera whoever it was and tell them where the phone call is."* Also, if a landline telephone is used to call a Vocera, no caller information is shown on Vocera, prohibiting the interruptee from perceiving the importance of the call. Participant 1 described it like this: "*If it's coming directly from a Vocera, we know who it is. If it's coming from a phone, you have no idea who it is."*

#4: The interruptee's availability

This proximal system factor is related to the component of Interruptee in the descriptive model, i.e., the interruptee's availability at the time of receiving a Vocera call. In many situations, nurses could be engaged in a complex task and have limited mental resources available for managing an interruption. At those times, interruptees are unlikely to accept a Vocera call. Participant 9 described it like this: "*The most important factor is where I am at and who am I with, or if I'm in the middle of doing something that will make my decision if I accept or decline.*"

The interruptee's availability depends on several moderator system factors. All of these moderator system factors are related to the component of Interruptee in the descriptive model, i.e., the interruptee's primary work at the time of receiving a Vocera call that influences their capability to attend to this interruption.

#4A: Direct patient care

Nurses perform a number of direct patient care tasks, such as suction, wound dressing change, medication administration, sterile procedures, etc. A nurse's attention is in high demand during these tasks, especially when a patient is unstable, intubated or restless. Therefore, interruptees may have limited mental resources available to manage a Vocera call, and thus unlikely to accept it. Participant 1 described it like this: "*if I'm in direct patient care, if I'm doing a procedure with a patient, if I am busy, and I need to be concentrating on what I'm doing, then I won't take it*."

#4B: Meeting

Nurses attend meetings as part of their work routine, such as the team-based bedside rounds and patient admission team briefings. Nurses may need to provide supplemental information and details about patient assessment and goals at the meetings. Therefore, interruptees need to pay full attention, leading them to be more resistant to taking a call during those types of meetings. Participant 8 described it like this: *"I think normally I would decline the call unless I knew that the patient was going to be going for some sort of a procedure. Because it's more important to listen to what's going on in rounds than it is to take the phone call."*

Participant 9 described it like this: *"I'll decline the call, because it's more important for me to listen to the debriefing from the surgeon and the anesthesiologist."*

#4C: Emergency or code situation

Emergency or code situations occur when a patient's condition deteriorates and requires intense nursing and/or healthcare team intervention. Dealing with an emergency or code situation is cognitively demanding, during which receiving a Vocera call can be a distraction and may compete with a nurse's already taxed attentional resources. Therefore, during emergency and code situations, nurses are likely to reject a Vocera call. Participant 2 described it like this: "*The only time I usually deny a call is if I am participating in something that would be considered a type of, I guess, emergency, if I'm doing something in an emergency situation or a code situation, then I'll just, I know that I can't be distracted from what I'm doing."*

#4D: Conversations with family

Nurses frequently talk to patients for educational and consoling (i.e., emotion-related tasks) purposes during their work. They might also have a conversation with a patient's parent talking about the patient's care plan. These conversations are extremely important and often emotional for the patient's families, as they are worried about their child. Responding to a Vocera call interrupts the conversation and would be perceived as rude. Therefore, during these situations, nurses are unlikely to accept a call. Participant 13 described it like this: "*if you were having a really important heart-to-heart conversation with a family member. Like say they're upset, and you're trying to do some teaching or some consoling, that that would not be a very good time to have an interruption."*

Participant 4 described it like this: *"You don't really want to be interrupted and asked about something if you're teaching a family something. I think that's just rude."*

#5: Vocera User Experience (UX)

This proximal system factor is related to the dynamic processes of interrupter and Vocera, as well as interruptee and Vocera, in the descriptive model. This system factor primarily influences nurses' performance. As a lightweight and hands-free technology, Vocera facilitates quick, easy, and efficient communication, especially for interrupters to initiate a one-to-one interruption. Participant 11 described it like this: "*The number one [of Vocera's influences on performance] is just to cut down on time. It is easy to press a button and call somebody versus going and dialing a number or typing, so they are useful."* However, Vocera UX may vary greatly depending on specific situations. There

were times when Vocera did not function well, leading to workflow inefficiency and frustrations. This frustrating process may influence nurses' decisions to use another method of the communication. Participant 13 described it like this: "*There are times when I've tried like two, I'll try sometimes two or three times, and then maybe I'll just try another person, another name, you know, another, or I'll look out in the hall and see if there's somebody that I can just grab. Or I'll say can you call so and so, you know, because there are other alternatives."*

The Vocera UX is dependent on several indicator or moderator system factors.

#5A: Battery

This moderator system factor is related to the component of Vocera in the descriptive model. The battery can run out during a nurse's 12-hour shift. A low battery is indicated by a sound emitted from the device, but that sound might be too low to be heard by the nurse, especially in the noisy and chaotic PICU environment. Additionally, nurses may be unfamiliar with what the sound signifies, causing them to ignore it. Lastly, when the battery runs out, Vocera turns off without notifying the user. Therefore, both the battery itself and the battery indicator may influence the Vocera UX for both interrupters and interruptees. Participant 14 described it like this: "*If you have a, you're using it a lot… your battery can [run] low, which can be inconvenient sometimes. Sometimes people don't realize like that it's [turned off]."*

#5B: Vocera voice recognition

This moderator system factor is related to the component of Vocera in the descriptive model. Voice recognition is a distinguishing feature of Vocera. To connect the call, the interrupter just needs to pronounce the first and last name of the interruptee. However, for some names, especially international names, Vocera has consistent trouble recognizing them. The interrupter may have to repeat the name several times, mispronounce the name in the way Vocera wants to "hear" it, or try to spell the name. Therefore, this issue may influence the Vocera UX, especially for the interrupters. Participant 11 described it like this*: "It doesn't always understand your voice, doesn't recognize what you're trying to say, so you have to say over and over some names, or it connects you to somebody you don't want to talk to, or, yeah, understanding, voice recognition."*

Participant 13 described it like this: *"I've learned that there's a name or two that I have to mispronounce it for it to understand me*."

#5C: Vocera's signal coverage

This moderator system factor is related to the component of Work Environment in the descriptive model, i.e., Vocera's wireless network inside and outside PICU. Certain locations in the PICU have been identified to have poor signal reception for Vocera. For example, Participant 8 described it like this: *"I thought it was a patient room at the high end that had kind of like a dead zone."* PICU nurses also go to locations off the unit with Vocera, such as the cafeteria, which may also have poor signal coverage, where the voice cannot be heard clearly, or the call may not even be able to get connected. Therefore, the

issue may impact the UX for both interrupters and interruptees. Participant 5 described it like this: *"I went down to eat lunch in the cafeteria and I didn't have a signal. My patient had some really significant blood pressure changes while I was unreachable, and so as soon as I walked into the zone I had all these calls and messages."*

#5D: Noise

This moderator system factor is related to the component of Work Environment in the descriptive model, i.e., background noise and patients' noise in the PICU work environment. Background noise might be due to alarms from patient monitors, ventilators, call lights, and people talking in the halls. Patients may generate noise because they could be crying or screaming at any moment. This noise constantly interferes with the voice recognition feature of the Vocera, as well as with the voice during conversation, impacting the UX for both interrupters and interruptees. Participant 3 described it like this: "*It's sometimes difficult having the Vocera understand, especially if there's a lot of background noise, your ventilators, the alarming, things like that. It's sometimes hard to get the Vocera to call who you're trying to call."*

Participant 12 described it like this: *"[During the call,] it just hears the voice of the baby at the same time it hears your voice and can't distinguish between one or the other."*

#5E: The healthcare protective clothing standards

This moderator system factor is related to the component of Culture/Policy in the descriptive model, i.e., during sterile procedures in isolation, nurses are required to wear gowns and gloves. For the interrupters, the gown covers Vocera, making a voice

command hard to be understood by Vocera. Also, wearing gloves, it is difficult to touch the main button on Vocera. For the interruptees, the gown over Vocera may muffle the caller's voice. Therefore, this issue may impact the UX for both interrupters and interruptees. Participant 3 described it like this: "*The gown will rub on the Vocera, and it's very difficult to hear people sometimes. I honestly have had to stick my face in my gown to talk to the Vocera so that it will understand what I'm saying to call a person."* Participant 14 described it like this*: "So gloves, yeah. I mean, if you're doing something that's dirty, it would be a barrier [to initiate a call], in general."*

#5F: Familiarity with other team members

This indicator system factor is related to the component of Interrupter in the descriptive model, i.e., the interrupter's knowledge of the names of the other team members in the PICU. Knowing another team member's name is a prerequisite to initiate a Vocera call, but is a challenge for nurses working in such large units, especially for new nurses. Therefore, for those who are not familiar with others in the PICU, the UX might be impacted, especially for interrupters. Participant 15 described it like this: "*I have to look out of the room [to try other interruption methods], because I don't know their name [so I cannot interrupt them using Vocera]."* Even for senior nurses, remembering all the residents' and fellows' names seems impossible because of the medical rotations every couple of months. Nurses have to develop their own memory aids for remembering names of coworkers. Participant 13 described it like this: "*When I see [residents and fellows] in the morning rounding, I try to write their name on my sheet of paper, their first and last name*."

The interactions of proximal system factors

Proximal system factors may interact in different forms – specifically, *overriding*, *balancing*, or *confirming* – influencing nurses' decisions regarding the use of Vocera for interruptions (See Figure 4.3). The nurses' performance depends on the decisions nurses make.

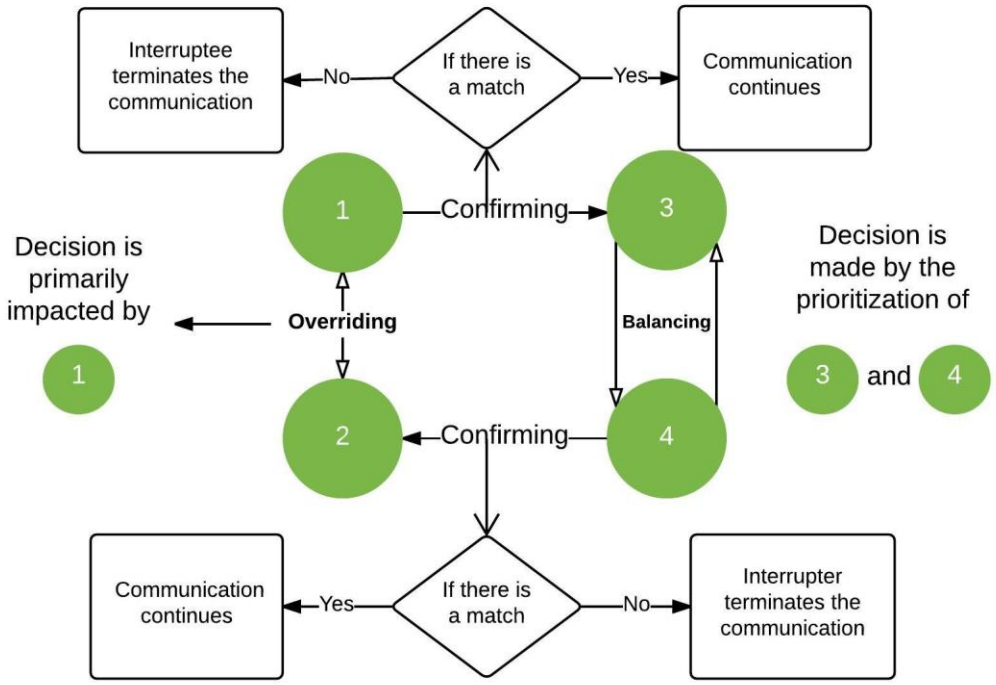

Figure 4.3: Proximal system factors interactions

One proximal system factor might *override* another, making one factor more dominant in influencing nurses' decisions and performance. System factor #1 (the nature of the interruption) may override #2 (perceived availability of interruptee) in certain situations. For example, if the interrupter has an urgent request for help or time-sensitive

information to deliver, they may initiate a call using Vocera immediately, regardless of their perception of the interruptee's availability. Participant 8 described how system factor #1 dominated the decision-making process regarding the use of Vocera for interruptions: *"If it was an emergency, then…I can just call one of the doctors and just, you know, tell them I need help."* This decision may influence the interrupter's performance positively by increasing communication efficiency, but at the same time may influence the interruptee's performance negatively by disrupting their workflow, especially when the interruptees happen to work on direct patient care tasks.

One proximal system factor might frequently be *balanced out* by another, leading to a decision based on a tradeoff of both system factors. Nurses have to carefully weigh the importance of different factors in specific contexts and their decisions might be nuanced and subtle. System factor #3 (perceived importance of the interruption content) is usually balanced out by #4 (the interruptee's availability). For example, interruptees evaluate these two factors simultaneously, prioritizing their current primary task with the potential interrupting task. Sometimes, the decision can be easy. However, when the interrupting task is perceived as almost important as their current task, their decision – in either direction – might be nuanced and subtle. Participant 13 described it like this: *"You just have to have a sense of which one is more urgent, finishing what I'm doing, or stopping what I'm doing to*." The decision may influence the interruptee's performance in different ways, either sacrificing the continuity of primary task workflow for better communication efficiency, or vice versa.

One proximal system factor might be *confirmed* by another. System factor #3 (the perceived importance of the interruption content) may be confirmed by #1 (the nature of the interruption). This might happen when an interruptee receives a call during a busy time inside the patient room, such as bedside rounding. The nurse may feel the call is important and therefore step out to accept it. Through a quick summary provided by the interrupter, the perceived importance of the interruption might be confirmed and the nurse may continue the conversation or go to provide help. Otherwise, the interruptee may terminate the Vocera call by telling the interrupter that they are not available to talk and resuming the primary task. Participant 8 described it like this: "*If I can, I just, you know, remove myself and step out closer to the door and see what my Vocera call is about and then make a decision…if I can leave and go help."*

Participant 13 described it like this: *[During rounds,] I usually just step away from the group to find out what it [the Vocera call] is. And then if it's something that can wait, I just say I'm in rounds right now. I'll get back to you."*

System factor #2 (perceived availability of interruptee) may be confirmed by #4(the interruptee's availability). This might occur when an interrupter initiates a Vocera call at a time that they feel the interruptee is available to talk through Vocera. Interrupters may confirm the interruptee's current availability at the beginning of the conversation. They may either continue the conversation or terminate the call based on the confirmation. Participant 6 described it like this: "*whenever I call somebody, I just ask, hey, are you busy? And if they say yes, then you just hang up and then call somebody else*."

Participant 2 described it like this: "*If the patient's crying or upset or something. And then somebody calls me [using Vocera], and I will answer, but most of the time, they hear that there's things going on, or I'll say I'm in a patient room, I'm busy."*

A failure to the confirmation may influence both interrupter's and interruptee's performance negatively, such as an inefficient communication and a disruptiveness to the workflow. However, the confirmation process is necessary to avoid additional costs because of the interruption.

Distal system factors

#6: Patient room comfort

This system factor is related to the component of Work Environment in the descriptive model, i.e., the comfort of PICU environment for patients and families. Vocera can sometimes sound loudly, thus disrupting the patient's rest. Therefore, when a patient is sleeping, the nurse may delay an interruption, going out of the patient room before initiating a Vocera call. Participant 5 described it like this "*I think to keep it quieter for the patient, the night nurses will step out of the room more to make [Vocera] calls."* When the interruptee receives a Vocera call inside the patient room, they may accept a call, but cover the speaker to avoid a loud voice and start the communication after stepping out. Participant 4 described it like this: *"I think if I'm in a room and I hear the Vocera like chime, and I want to keep it quiet, I'll like then cover my speaker and then look at the name and then walk out of the room if I want to take the call."* The decision may negatively influence nurses' performance in some aspects, such as a delay of their

workflow and communication. But the decision may also positively influence other aspects of nurses' performance, such as providing quality patient care.

#7: Patient's privacy

This system factor is related to the component of Culture/Policy in the descriptive model, i.e., compliance with regulations that protect patients' privacy. Nurses may receive calls in public places, such as the hallway, break room, and cafeteria. Nurses may also receive calls in one patient's room regarding another patient. The conversation might be overheard by someone around the nurse; therefore, a Vocera communication presents the risk of violating the patient's privacy. To protect privacy, immediately after accepting a Vocera call, the interruptee may let the interrupter know their current place, in an effort to not violate the regulations. Participant 4 described it like this: "*I'm down in the cafeteria and somebody's trying to call me, I almost always make sure to say to the person who's calling me, hey, I'm down in the cafeteria right now, what can I help you with? And then they'll be like, oh, never mind*." If the interruptee is inside a patient's room with the parents, they may need to step out of the room first and then engage in the Vocera conversation. Participant 10 described it like this: "*if there are other people in the room, then, and you're in isolation, you probably should go out and just answer the phone so you're not, you know, ruining something with someone's privacy or something."* Similar to distal system factor #6, the decision may negatively influence nurses' performance in the aspects of workflow and communication efficiency, but may positively influence the quality of patient care.

#8: Culture of PICU

This system factor is related to the component of Culture/Policy in the descriptive model, i.e., the way things are done in a particular work system. In the PICU, one aspect of the culture is Vocera is frequently used as an interruption mediating tool. In a work system that sets the expectation to use Vocera for communication, nurses are able to interrupt others and communicate via Vocera. This culture facilitates easy communication between nurses and other staff in the team, as well as the efficient patient care. While both PICU floors appeared to have the culture of using Vocera, participants did mention culture differences outside of the PICU. For example, the Hematology, Oncology, Transplant (HOT) unit stopped using Vocera shortly after its implementation because that unit's culture did not support its use. Participant 9 from Cardiac surgical ICU described it like this: *"for the most part, you know, people use them on a fairly regular basis".*

Participant 1 from the general medical ICU described it like this: *"We use it frequently. I think it's appreciated. People like it. We're respectful with it…I think it promotes patient care, helps with patient care when it works."*

Participant 2 floated to HOT unit once and described it like this: "*I think the HOT Unit tried them for a little while…they all didn't like them."*

#9: Training

This system factor is related to the component of Culture/Policy in the descriptive model, i.e., guidance to standardize the use of Vocera for interruptions. Nurses received training on using Vocera when they first started working, and no refresher training was

provided. In a work system that sets the standardization of the use of Vocera for interruptions, the best use of Vocera at appropriate situations may be facilitated. Nurses expressed little need for additional training, as they felt the device is simple enough to use. Participant 11 described it like this: "*It's user friendly, so, yeah, I wouldn't need any [organizational] support."*

Participant 4 described it like this: "*I think I just picked up on it from watching other nurses use it and things like that. It's very user friendly. It's not, it doesn't take too much time to learn."*

However, many participants were unaware of some of the functionality (new and old) that Vocera has to offer. Additionally, there is no training provided as to when to use Vocera. This means that the use of Vocera is not standardized across the units to be used in the best way. Participant 3 described it like this: "*I feel like ever since we first got them, there hasn't been a lot of extra education on additional features, necessarily.*"

Participant 4 described it like this: "*We haven't had like a reminder of like how to use them the best, what, you know, maybe like a Vocera etiquette, and why would you use your silence versus not? It works best up here."*

4.4 Discussion

This study aimed to understand system factors within HCDs interruption dynamics, and their role in influencing nurses' decisions and performance. Using qualitative research methods, we identified different types of system factors distributed at different levels. Based on activity theory, we created a descriptive model of HCD interruption dynamics, showing the causal paths and mechanism of system factors,

especially the interactions of proximal system factors, the inputs of indicator and moderator system factors to proximal system factors, and the distant influence of distal system factor further down the causal chain. The results of this study extended the findings on nurses' face-to-face interruptions (Rivera, 2014), and HCD-mediated interruption dynamics (Yang & Rivera, 2015). This study also provided evidence that system factors in HCD interruption dynamics influenced nurses' decisions and performance in ways that are more complicated than previous literature has depicted.

Vocera as a tool for mediating interruptions

Interruptions occur frequently in the healthcare work system, especially in critical care settings such as the ICU (Alvarez & Coiera, 2005; Gupta et al., 2013). Nurses in the PICU are more vulnerable to fatigue and excessive workload, as they provide care to patients at high levels of acuity (Montgomery, 2007). Responding to unplanned interruptions further complicates their workflow (Krichbaum et al, 2007). A disruptiveness or loss of concentration on the primary task may increase the potential for medical errors and infections (McGillis Hall et al., 2010). However, it is not reasonable to eliminate all interruptions in this work system, because interruptions could be value-added involving essential patient care communication (Rivera-Rodriguez & Karsh, 2010).

Vocera is HCD that has been implemented in healthcare environments like the PICU to improve clinical communication (Wu et al., 2012). Research has shown that the implementation of Vocera actually increases the frequency of interruptions (Ernst et al., 2013). However, Vocera does in fact support the interruption process by reducing the

effort required for interruptions. Based on the *principle of least collaborative effort*, people try to minimize their collaborative efforts from the initiation of a communication to a mutual understanding (Clark & Wilkes-Gibbs, 1986). Vocera facilitates achieving this principle during the interruption process. With a Vocera, the interrupter's effort to initiate an interruption may be reduced because they can easily get a hold of another person at any location. Interruptees can control which Vocera call to accept and when to accept the call based on the caller's name and expectations as well as their current availability. Compared to face-to-face interruptions, interruptees are more comfortable declining a call if they perceive a request unreasonable, which is similar to the way to manage interruptions mediated by telephone (Furnham, 1982). People can hear each other and communicate in real time in an ordinary sequence without a delay (Clark & Brennan, 1991). This keeps the interrupter's workflow consistently and facilitates the allocation of interruptee's cognitive resources to their primary tasks.

Despite the potential benefits in supporting interruptions, Vocera does not replace other interruption methods. The choice of Vocera is very dependent on the specific context and the easiness and convenience. For example, for infection prevention purposes, isolation rooms are specifically designed for high-risk patients admitted to the PICU. The rooms have two sets of doors with an anteroom in between that protects the patient's environment from the hallway. Inside the patient room, it is nearly impossible to seek help from people in the hallway, because both sets of doors are closed. To go out of the room to find someone, the interrupter must remove their personal protective equipment by de-gowning, taking off their gloves, washing their hands and opening each

set of doors. This process is very inconvenient, adding to an already demanding workflow. Therefore, in isolation rooms, when nurses need supplies or help, they often choose to use Vocera as the method to interrupt others. This is just one example of a situation where Vocera is generally the preferred interruption mediating tool. In some other situations, a face-to-face interruption, a paging message, or a telephone conversation might be a better choice. For example, when giving an important update of a new patient admission, the charge nurse may walk to a staff nurse to have a face-to-face conversation. When there is a need for sending a group message to several people simultaneously, nurses generally use the paging system that has a global message function.

If Vocera has been selected as the method for an interruption, the realization of its full potential also depends on the indicator and/or moderator system factors that influence the proximal system factor #5 (Vocera UX). These factors could be related to the Vocera itself, such as its voice recognition performance or battery indicator. They could also be related to the interrupter and interruptee, the work environment, and culture/policy. Therefore, to improve the support of interruptions in the nursing work system, it is not enough to just enhance the reliability and adaptability of Vocera itself.

We must take a macroergonomic perspective to examine the interactions nurses have with Vocera and address any incompatibilities of the system factors, between the indicator or moderator system factors (#5A-F) and proximal system factors (#5). The macro-level method is useful when trying to avoid unintended consequences while implementing new technologies or devices in healthcare, or any complex system (Karsh,

2004; Yang, Rivera, Fortier, & Abernathy, 2014). For example, per protocol, Vocera must be covered by an isolation gown. While the regulation serves a purpose from an infection prevention perspective, the voice of caller can come across muffled and unintelligible, thus negatively influencing the Vocera UX. One solution to mitigate this incompatibility is to redesign the gowns by using a material that has better sound penetration. Another benefit of Vocera is its voice command: the user states the recipient's name to initiate a Vocera interruption. However, the composition of the healthcare team is constantly changing, making it difficult for nurses to know all of the members' names. Thus, incorporating redundancy by designing multiple ways to initiate a Vocera call might be an effective solution to this issue. For example, hot keys, triggered by voice, may be customized by the nurse and set up before the nurse's shift: saying "one" may directly connect a nurse that she prefers to seek help with; saying "two" may connect to a charge nurse directly; and etc.

Complications of the cost-benefit analysis

The decision-making process to initiate an interruption using Vocera is complicated. A decision is made with the intent to have the best performance possible. Previous research has shown that interrupters initiate an interruption based on a quick cost-benefit analysis, making a comparison of the urgency and importance of the interruption content with the potential disruptiveness to the interruptee's workflow (Rivera, 2014). Visual cues embedded in the work environment may suggest the interruptee's engagement of a risky task during which interruption is only be permitted for an urgent issue communication (Coiera, 2012). However, a device-mediated

interruption involves only the auditory modality (Magrabi, Li, Dunn, & Coeira, 2011), lacking visual cues showing the interruptee's current situation (Wiberg & Whittaker, 2005). The lack of visual cues makes the cost-benefit analysis process complicated. For example, before a Vocera call is connected, the interrupter have limited knowledge of the interruptee's primary task which indicate the interruptee's availability, such as performing direct patient care (#4A), attending a meeting (#4B), dealing with an emergency or code situation (#4C), or having a conversation with a patient's family (#4D). As a result, the cost-benefit analysis is almost based on estimation of the interruptee's availability before the Vocera call is connected. Immediately after the call is connected, a quick negotiation process between interrupter and interruptee can help interrupters gather knowledge of the interruptee's availability (#4). Based on the new information, interrupters can conduct another cost-benefit analysis that is more accurate, and make a more informed decision, either to continue the conversation, or to terminate the call.

Similarly, the decision-making process to manage an interruption using Vocera is also complicated. When the interrruptee receives a Vocera call, they need to decide whether to accept or decline a call based on a cost-benefit analysis (Rivera, 2014). While the importance of an interruption can be estimated by several indicators, such as an interruptee's expectation of a Vocera call (#3A), the role of the caller (#3B), and the interuptee's own nursing role (#3C), without visual cues, these indicators may not always be accurate (#3D). Immediately after the call is connected, a quick negotiation process between interrupter and interruptee can help interruptees gather knowledge of the

urgency of an interruption from the interrupter's perspective (#1). Based on the new information, interruptees can conduct another cost-benefit analysis by comparing their primary task with the importance of the interruption. Based on the analysis, they can make an informed decision to continue the communication or terminate the interruption.

Even if a quick negotiation process can help interrupters and interruptees gather knowledge for the cost-benefit analysis, an important Vocera call may be declined by an interruptee beforehand, losing the opportunities for negotiation. Moreover, a quick negotiation process may still disrupt the interruptee's workflow, because it might be hindered by a slow communication grounding process via Vocera (Clark & Brennan, 1991). A person's voice through Vocera tends to be more mono-tone than the real face-to-face communication because of the audio signal processing (Casali, 2012; Yang & Rivera, 2015). The voice might lose the fluctuation and pitch indicative the interrupter's emotions, i.e., the affective cues (Rivera, 2014). The lack of affective cues may reduce the effectiveness and efficiency of communication and reach a mutual understanding of the interruption's urgency and the interruptee's availability.

Thus, the lack of visual and affective cues is the biggest challenge during the use of Vocera as an interrupting mediating tool. In order for Vocera to better support interruptions, systematic design of a nursing work system are recommended to resolve this challenge. For example, the interruptee's current status indicating their current availability may be shown on the interrupter's Vocera screen (#4A-D). This can be achieved by an awareness indicator, similar to what was presented in the prototype of Working Awareness Interruption Tool (WAIT) in the context of air traffic control

(Alqahtani & Histon, 2012). Interruptees can easily set their status by a voice command to Vocera, for example, saying to Vocera: "Status: direct patient care". Then when an interrupter is calling this person, in the phase of confirming the name of the interruptee, Vocera might say: "You are referring to Susan Zhang. Susan Zhang is currently in direct patient care. Do you want to make the call?" Based on this information, an accurate cost-benefit analysis can be conducted immediately before the Vocera call is connected. The awareness indicator could be integrated with a location identification tool, such as Radio-frequency identification (RFID), which was suggested by Yang and Rivera (2015). An interruptee's location is a strong indicator of availability; for example, in a patient's room generally equates to performing direct patient care. The location identification tool could be used as a backup of the indicator, especially when the interruptee is too busy to set up the awareness indicator. Similarly, the importance or urgency of an interruption may also be delivered to the interruptee when initiating the interruption. For example, the method to initiate a Vocera call may be designed in such a way as to differentiate the importance of interruptions, for example, by the number of touches on the button. If the interrupter is in need of urgent help, they may touch the main button twice, indicating the interruption is important. The interruptee may receive that call by hearing music with hurried tempo and vibration. In this way, an accurate cost-benefit analysis can be completed before the call is connected.

To implement these suggestions, organizational support in the form of formal training is necessary for nurses to understand the new features and how they should be used. To avoid additional workload and unintended consequences, nurses could be

trained using simulation to become familiar with situations where the awareness indicator and the interruption urgency function should be used in order to facilitate the interruption process (Lateef, 2010). Training using high-fidelity simulation in healthcare can also facilitate a work culture to improve patient outcomes and safety (Zigmont, Kappus, & Sudikoff, 2011).

The importance of context in the interruption dynamics

The decisions nurses make regarding the use of Vocera for interruptions can be nuanced and subtle. For example, nurses may either accept a Vocera call or reject a call when the cost-benefit analysis suggest an indefinite or opposite decision. This implies that nurses' decisions and performance may be influenced by the complex and dynamic contexts. In this study, we found that context-based distal system factors, and perhaps their connections with other system factors, played an important role that influences nurses' decisions and performance distantly. This is consistent with *phenomenologically situated cognition theory*: for human behavior and decision-making, what looks to be easily standardized is actually much more situationally informed (Suchman & Reconfigurations, 1987).

Distal system factors may connect with other system factors influencing the nurses' decisions. For example, when a nurse receives a Vocera call in the isolation room, they may de-gown and go out of the room to start the conversation, even if the call can be easily answered inside the room. The decision might be made for the purposes of not disrupting a sleeping patient. In this context, not disrupting the patient's sleep to allow them stay comfortable (#6) is set as a higher priority than any other system factors,

even the proximal ones which generally have a more direct influence on nurses' decisions.

The connection of distal system factors and proximal system factors may also influence nurses' performance. A particular aspect of the culture in PICU (#8) is the way to assign patient rooms. For example, in this PICU, charge nurses generally assign the most critical patients to rooms that are further away from the central nursing station. However, these rooms happen to have poor Vocera connectivity. The connection of the culture of PICU (#8) and poor Vocera UX (#5) amplified the influence on nurses' performance: nurses in need of the most help may not be able to reach others using Vocera. These consequences may be relieved by changing the culture of patient assignment, if the signal issues cannot be addressed easily.

Limitations of the study

We implemented strategies to ensure research rigor; however, limitations for this still exist. Table 4.5 summarizes the limitations of this study, as well as the explanations and efforts made by researcher to minimize their negative influences on the research rigor.

Table 4.5: Study Limitations

	Description	**Explanations**	**Efforts**
1	Study was only conducted in one hospital.	Due to resource constraints, we are not able to conduct research in multiple hospitals to further ensure the transferability of the results.	Transferability was enhanced by sampling participants from two different PICUs. Also, transferability of a qualitative study can be determined by audience, based on the fit of their systems (Malterud, 2001).

			This limitation can also be improved by a future large-scale study.
2	Observation is conducted by one observer; interview coding is conducted by one coder.	Due to resource constraints, we are not able to have an additional observer for data collection and coder for data analysis, which may introduce bias. However, single observer and coder may increase the consistency of data collection and analysis. The reliability can be ensured by having an additional researcher critically reviewing the coding schemes (Campbell, Quincy, Osserman & Pedersen, 2013). Coding by one researcher is also an accepted method for a qualitative study in human factors research with similar scope (Rivera, 2014).	To reduce potential bias, we conducted observation based on a standardized observation template. We conducted three rounds of coding, and each round has been critically reviewed by a senior human factors researcher. An audit trail recorded all decisions made during the data analysis process. This all helped ensure the reliability of this study (Rodgers & Cowles, 1993).
3	Observations by shadowing were restricted by the layouts in the PICUs and Hawthorne effects (Adair, 1984).	The observer had to stand outside the patient room (in the anteroom) if the patient was in isolation for infection prevention purposes. Therefore, some events may have been missed in real-time due to the distances between the observer and the participating nurse. Moreover, nurses might alter their behavior as a result of being part of a study (Adair, 1984).	Research methods triangulation may facilitate to capture all possible scenarios (Creswell, 2013). Also, in the future, this limitation can be addressed using other methods of observation, such as video recording.
4	The interview is retrospective, and the participants were not the same as the observed participants, resulting in abstract situations.	Due to the regulations in the hospital and nurses' availability, conducting interviews immediately after the observation was not a possibility.	We used scenarios to facilitate the interviews so that the nurses' responses are not merely abstract situations.

4.5 Conclusion

This study took a systems approach to explore system factors at different levels that impact the HCD interruption dynamics. Based on activity theory, a descriptive model of HCD interruption dynamics was developed, showing the proximal system factors, indicator and moderator system factors, distal system factors, and their causal chains and mechanisms within the HCD interruption dynamics. These system factors impacted HCD interruption dynamics and influenced nurse' decisions and performance regarding the use of HCDs. Nurses' decisions and performance were dependent on the context. The indicator or moderator system factors provided partial inputs and contextual circumstances to proximal system factors, and the distal system factors, distributed in the environmental and organizational context, influenced the nurses' decisions and performance further down the causal chain. Because of the lack of visual and affective cues, nurses have to rely on a negotiation process after a call is connected to gather knowledge of the nature of an interruption and the interruptee's interruptibility. In sum, HCDs provided benefits to nurses by reducing their efforts to initiate and manage interruptions; however, the potential of HCDs has not been fully utilized from a macroergonomics perspective, because of the unintended consequences and incompatibilities with other interacting components in the sociotechnical system. Redesigns of the system were suggested based on the findings: the improvement of the Vocera itself, as well as building a work system culture to facilitate the best use of Vocera and designing a training program to enhance the newly suggested features of Vocera. Future research may need to validate the descriptive model of HCD interruption

dynamics model in a larger scale study, evaluate the system design recommendations, and understand the effects of individual and interacting system factors on decisions and performance in a quantitative manner.

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CHAPTER 5: CONCLUSION

The overall objective of this dissertation was to understand HCD interruption dynamics in nursing work systems. The results revealed the multidimensional complexity of HCD interruptions situated in the real-world context of nursing work systems. The outcome expanded the representation of the interruption problem space, changed the way we think about effective interventions, and facilitated the joint optimization of system inputs from the social, technical, and cultural subsystems.

The first study used a socio-technical system approach to study the HCD interruption dynamics in acute care settings. This observational study revealed the major differences between HCD-mediated interruption dynamics from the existing knowledge of face-to-face interruptions. It identified the role of HCDs as facilitators to advance nursing work in interruptions dynamics, i.e., they improved nurses' workflow continuity, efficiency of nursing communication, and flexibility in responding to interruptions. However, it also identified the role of HCDs as barriers to limit the work performance, such as the interrupter-oriented nature of the HCD-mediated interruptions, the potential delay of information delivery, and the potential inaccuracy of information delivery. Based on the findings, recommendations for product design and policy development were made.

The second study explored system factors that influence nurses' decisions and performance regarding the use of HCDs. The observation and interview data collection and analysis were guided by the meso-ergonomics paradigm and activity theory. The research identified a number of system factors in HCD interruption dynamics. A

descriptive model of the dynamics exhibited the integrated causal chains of these system factors. Based on the findings, we recommended integrating visual and environmental cues into the design of HCDs to support an accurate cost-benefit analysis before the call is connected, accompanied with organizational-level interventions.

This dissertation is significant because of its potential in improving the quality and safety in the healthcare work systems. This is the first research study guided by theoretical frameworks from a systems perspective to understand the complexity of interruptions in the real world. The study extended the knowledge of face-to-face interruptions to device-mediated interruptions. This is also the first study that explored the influence of system factors and their interconnectivity on nurses' decisions and performance during the interruption process. The understanding of HCD interruption dynamics changed the way we think about effective interventions by facilitating the joint optimization of nursing work systems. The results of this study may also provide a framework for future Industrial Engineering researchers studying interruptions in healthcare. For example, based on Figure 4.3, the proximal system factors interactions, Industrial Engineers may be able to develop algorithmic models, for developing a system with adaptive automation, in which the interrupters and interruptees can make the most optimized decisions.

The limitations of this dissertation were discussed in each chapter respectively, including the potential in missing recently published studies in the previous reviews and summaries, the relatively small scope for participant sampling, the single researcher collecting and analyzing the data, the restrictions of the shadowing method, and the

retrospective nature of the interview method. Efforts were made to overcome the limitations by maintaining high standards for research rigor, which included continuous review of recent published papers, purposeful sampling strategies, research methods triangulation, observation and interview protocols, audit trails, and expert member check of the data analysis.

This dissertation is an exploratory study of HCD interruption dynamics. Due to the context-dependent nature of this qualitative research, the purpose was not to generalize the research outcomes. But the study provides sufficient descriptions of the context to facilitate transferability, and the applications of the results can be determined by readers. For example, some findings may be applied to other healthcare settings for the improvement of HCDs in supporting interruption management. Also, some findings may be applied to the design of other interruption-mediating tools in the healthcare environment, such as wearable computing devices. Some findings may be applied to other interruption-laden work systems mediated by communication tools, such as firefighter or police work systems. Moreover, the research methods and procedures presented in this dissertation can be applied to other human factors research, especially for analyzing problems in complicated work systems.

The new perspectives and the descriptive model of HCD interruption dynamics derived from this exploratory research has opened up the opportunities for future research. Below is a list of future research suggestions.

- Implement and evaluate the recommendations provided in the dissertation;

- Continue the HCD-mediated interruption research in a larger scale study in different types of hospitals and units;
- Understand how other types of hands-free/wearable devices, such as head-up displays or glasses, can enhance the communication among healthcare professionals, and compare that with the results of this dissertation;
- Develop interactive technologies, such as the surface computing and augmented reality to facilitate the support of interruptions, especially to support a simplified negotiation process between interrupters and interruptees;
- Evaluate the effects of each system factor and their interactions on the nurses' decisions and performance using a mixed research method study design.

APPENDICES

Appendix A: Observation Template

Time	Interruption Event Description	Vocera UX	Cognition information	Team information	Organization information	Nurse' Decisions	Nurses' Performance

Appendix B: Interview Protocol

Overarching Themes	Questions
The role of Vocera as a tool to complete nursing work throughout the day (UX Level)	Can you describe your experience using Vocera? Probes: Do you feel Vocera is easy to use during different situations? In what patient care situations is Vocera easy to use? In what patient care situations is Vocera difficult to use? • In general, how does Vocera compare to other communication devices? How does Vocera compare to face-to-face communication? • Why would you choose to use Vocera to communicate to someone versus another communication device (phone, pager)? How does Vocera impact your completion of nursing tasks during the day? Probes: • How does Vocera support your task completion? What kind of tasks does Vocera support? • How do you use Vocera to initiate or receive a call? How do you use Vocera to receive or receive a call? How does the use of Vocera fit in your workflow?
The mental demands of using Vocera (Cognitive level)	In which situations do you feel using Vocera is mentally challenging for you? Probes: • During which primary tasks would you feel receiving and accepting a Vocera call is more challenging for you? • Compared to other ways of interrupting (phones, pagers, face-to-face), do you feel the use of Vocera needs more of your focus and attention to initiate a call? Do you feel the use of Vocera needs more of your focus and attention to receive a call? • Can you describe a situation where you manage two or more interruptions at the same time? How do you deal with that situation?
The role of Vocera in facilitating team work (Team level)	What do you consider when you are going to interrupt someone via Vocera? Probes: • Scenario: A patient is newly admitted in isolation and you are working with the critical care physicians for team briefing and setting up the admission process. You need to push the pharmacist for an order. What do you consider when you receive a Vocera call from others? • Scenario: During a bed-side rounding, you receive a call

	from the unit manager/pharmacist/other nurse.
Organizational effects with the implementation of Vocera (Organizational level)	What type of organizational support have you received related to using Vocera? (Examples: training policies & procedures, JITs)? How do you deal with patient privacy concerns when using Vocera? How does the work environment impact the use of Vocera? How does the culture in your work unit influence the use of Vocera?
Demographics	1. Years of Age:_____ 2. In which group do you mostly place yourself: a. African American/Black b. American Indian/Alaskan Native c. Asian/Pacific Islander d. Caucasian e. Hispanic/Latino f. Other_____ 3. How many years you have worked at CHW? 4. How many years have you worked as a nurse? 5. How many years have you worked with a hands-free communication device (Vocera)? 6. Have you had experience with other hands-free communication device in your life except Vocera? 7. Have you had experience with a hands-free communication device in your nursing work other than Vocera?

Appendix C: Observation Events and Matrix

1. Vocera interruption events:

#1: A nurse calls the pharmacist to push for a medication order. She immediately talks to the pharmacist when the call is connected.

#2: A nurse tries to call another nurse, and asks her to bring something. She does not make the call successfully because the other nurse put Vocera offline. She delays the interruption. Finally, the message is delivered to another nurse that comes to help the nurse.

#3: A nurse receives a call from the secretary while taking care of the patient. She accepts the call and is told there is a call for her from the welcome center. She asks secretary to transfer patient's call to her Vocera.

#4: A nurse receives a call when charting inside the room from the unit secretary. The nurse accepts the call, being told the grandparents come to visit.

#5: A nurse makes a Vocera call to the charge nurse of this floor when she sent a blood sample. She tells the charge nurse that she will take a lunch break and asks the charge nurse who will take her shift.

#6: A nurse (charge nurse) uses Vocera to call a supervisor in another floor in the patient room, to report the patient number on this floor, and the number of nurses in this floor during the night.

#7: When the charge nurse goes into a patient room, she receives a call from the unit secretary. She cannot hear clearly a number for returning a call due to signal issues. She goes out of the patient room for the conversation.

#8: When the charge nurse goes into the patient room for help during a new patient admission, she receives a call from Vocera from the charge nurse in another unit. She steps out of the patient room and tells the caller that she is busy. She hangs up the call and goes back to the room.

#9: A charge nurse is working on the night shift assignment. She receives a Vocera call from a charge nurse of the other unit. They talk about floating nurses to this unit.

#10: While the nurse is on a telephone call (listening to a machine recorded message) at the central desk, a Vocera call comes in. She hangs up phone, accepts the Vocera call and immediately starts talking.

#11 After a patient is admitted, a nurse is working on setting up the Intravenous (IV) infusion pump. She receives a Vocera call from the HUC. She stops setting up the pump and accepts the call. The call is from the patient's parents, calling about visiting. The nurse tells the HUC that the parents need to wait for several minutes; then she hangs up the call and resumes what she was doing.

#12: The nurse is at the final step for patient admission. The nurse uses Vocera to call the unit secretary and says the patient family can come.

#13: When the nurse is cleaning the patient's mouth in isolation room, he receives a Vocera call. He stops the task, reverses his position, and uses the only one free hand to move Vocera towards himself (the other hand is to hold the tube of the mouth cleaning equipment). The call is from HUC about blood ready from the blood bank and its expiration.

#14: When charting, the nurse uses Vocera to call another nurse to come for help. The call is accepted but is told by the other nurse that she is busy and cannot provide help. The nurse terminates the call.

2. Interruption Events Matrix

	A. Prior to connection of Vocera call	**B. After Vocera is connected**
1. Interrupter	Initiate a Vocera call immediately: #1, #5, #6, #12, #14 Delay a Vocra call: #2 Use another method for communication: #2	Start to talk to the interruptee about the interruption content: #1, #5, #6, #12 Terminate the Vocera call: #14
2. Interruptee	Accepts a call: #3, #4, #7, #8, #9, #10, #11, #13 Declines a call or reject a call*	Immediately answer questions and provide help: #3, #9, #10, #11 Step out of the patient room and start the conversation: #7 Terminate the Vocera call: #8

*No nurse declines or ignores a Vocera call based on the observation. But that is an option of Vocera and was mentioned by nurses based on interviews. This might be due to: (1) With the presence observer, they might act differently and accept most of the calls that may be rejected; (2) Observer has to stand in the anteroom outside the patient room if the patient is in isolation, which increased the possibility to miss an event, since declining a call is quick and observer cannot hear clearly about everything inside the room.