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Improving Antibiotic Resistant Infection Transmission Situational Awareness in Enclosed Facilities with a Novel Graphical User Interface for Tactical Biosurveillance

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**IMPROVING ANTIBIOTIC RESISTANT INFECTION
TRANSMISSION SITUATIONAL AWARENESS IN ENCLOSED
FACILITIES WITH A NOVEL GRAPHICAL USER INTERFACE
FOR TACTICAL BIOSURVEILLANCE**

by

Valeriya V. Kettelhut

A DISSERTATION

Presented to the Faculty of
The Graduate College in the University of Nebraska
In Partial Fulfillment of the Requirements
For the Degree of Doctor of Philosophy

The Department of Surgery
Biomedical Informatics Graduate Program

Under the Supervision of Professor James McClay

University of Nebraska Medical Center
Omaha, Nebraska

June, 2015

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ABSTRACT

IMPROVING ANTIBIOTIC RESISTANT INFECTION TRANSMISSION SITUATIONAL AWARENESS IN ENCLOSED FACILITIES WITH A NOVEL GRAPHICAL USER INTERFACE FOR TACTICAL BIOSURVEILLANCE

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University of Nebraska Medical Center, 2015

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Serious challenges associated with antibiotic resistant infections (ABRIs) force healthcare practitioners (HCPs) to seek innovative approaches that will slow the emergence of new ABRIs and prevent their spread. It was realized that traditional approaches to infection prevention based on education, retrospective reports, and biosurveillance often fail to ensure reliable compliance with infection prevention guidelines and real-time problem solving. The objective of this original research was to develop and test the conceptual design of a situational awareness (SA)-oriented information system for coping with healthcare-associated infection transmission.

Constantly changing patterns in spatial distribution of patients, prevalence of infectious cases, clustering of contacts, and frequency of contacts may compromise the effectiveness of infection prevention and control in hospitals. It was hypothesized that providing HCPs with a graphical user interface (GUI) to visualize spatial information on the risks of exposure to ABRIs would effectively increase HCPs' SA. Increased SA may enhance biosurveillance and result in tactical decisions leading to better patient outcomes. The study employed a mixed qualitative-quantitative research method encompassing conceptualization of GUI content, transcription of electronic health record and biosurveillance data into GUI visual artifacts, and evaluation of the GUI's impact on HCPs' perception and comprehension of the conditions that increase the risk of ABRI transmission.

The study provided pilot evidence that visualization of spatial disease distribution and spatially-linked exposures and interventions significantly increases HCPs' SA when compared to current practice.

The research demonstrates that the SA-oriented GUI enables the HCPs to promptly answer the question, “At a given location, what are the risks of infection transmission there?” This research provides a new form of medical knowledge representation for spatial population-based decision-making within enclosed environments. The next steps include rapid application development and further hypothesis testing concerning the impact of this GUI on decision-making.

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LIST OF ABBREVIATIONS

ABR	Antibiotic resistant
ABRIT	Antibiotic resistant infection transmission
ABRITSA	Antibiotic Resistant Infection Transmission Situational Awareness
ABRO	Antibiotic resistant organism
C. difficile	Clostridium difficile
CDC	Centers for Disease Control and Prevention
CFIR	Consolidated Framework for Implementation Research
CQHCA	Committee on Quality of Health Care in America
CRE	Carbapenem-resistant Enterobacteriaceae
CSE	Cognitive Systems Engineering
DHHS	The U.S. Department of Health and Human Services
EHR	Electronic health record system
ESBL	Extended-spectrum β -lactamase-producing Enterobacteriaceae
HAIs	Healthcare-associated infections
HCPs	Healthcare practitioners
HITECH	Health Information Technology for Economic and Clinical Health Act
IOM	The Institute of Medicine
IRB	Institutional Research Board
IT	Information technology
Level 1 SA	First level of Situational Awareness
Level 2 SA	Second level of Situational Awareness

Level 3 SA	Third level of Situational Awareness
MDRO	Multi-drug resistant gram-negative organisms
MRSA	Methicillin-resistant Staphylococcus Aureus
PRISM	Practical Robust Implementation and Sustainability Model
SA	Situational Awareness
GUI	Graphical User Interface
VRE	Vancomycin-resistant Enterococci
XLS	Microsoft Excel® Spreadsheet File

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- C- Patient is not a carrier of ABRO
- I+ Patient receives antibiotics (IV/PO)
- I- Patient does not receive antibiotics
- HC+ High contact patient (requires external assistance)
- HC- Not high contact patient (independent or requires mild assistance)

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CHAPTER 1: CREATING OPPORTUNITIES FOR CONTAINMENT OF RESISTANT INFECTION TRANSMISSION WITH INFORMATION TECHNOLOGIES

1.1. Challenges Associated with Antibiotic Resistance in Hospitals

Regardless of the advances in infection control systems, the incidence rates of healthcare-associated infections (HAIs) remain relatively unchanged.[1] HAIs have a significant impact on morbidity and mortality, and continue to drive the cost of healthcare, attributing approximately 45 billion dollars each year.[2] Infections caused by antibiotic-resistant organisms (ABRO), such as Methicillin-resistant *Staphylococcus Aureus* (MRSA), Vancomycin-resistant *Enterococci* (VRE), multi-drug resistant gram-negative organisms (MDRO), and recently emerging Carbapenem-resistant *Enterobacteriaceae* (CRE) are increasing at an alarming rate, aggravating the challenges with infection prevention.[3-10] According to the Centers for Disease Control and Prevention (CDC), antibiotic resistant (ABR) infections cause two million illnesses and approximately 23,000 deaths each year in the United States. The World Economic Forum declared that antimicrobial resistance is now a global threat.[3]

Barriers to Compliance with Infection Prevention Guidelines

Antimicrobial overuse in humans and farm animals intensifies the selection of resistant strains while substandard infection control in healthcare settings facilitates its spread from human to human. Hospitals are a major source for the emergence, selection, and spread of multidrug-resistant organisms.[5] According to the World Health Organization (2005), low compliance with infection prevention and control evidence-based guidelines is one reason that five to ten percent of patients admitted to hospitals acquire at least one HAI.[5, 11] In 2012, The U.S. Department of Health and Human Services (DHHS) also reported low adherence to broad-based HAI prevention practices that must be employed consistently by a large number of health care personnel.[12] Several studies provide evidence on the underlying reasons for low compliance such as understaffing, poor design of facilities, failure to apply behavioral theories, and insufficient reinforcement.[13, 14] Lack of a link between infection surveillance information and infection prevention contributes to the inefficient management of infection prevention activities at a healthcare

delivery level.[5] Evidence also shows that many guidelines are impractical, while strategies aiming at improving adherence are short-lived and unsustainable.[15, 16] Therefore, a system that would generate evidence on what works and what does not should be established as a normal part of healthcare in the U.S.[17] For this, the CDC proposed integrating electronic biosurveillance data and big data available in local EHR systems into operations to create opportunity for innovative decisions (Table 1.1).

Table 1.1: The CDC Goal for Creating Opportunities for Infection Prevention

Goal	Rapidly Detect Patterns and Trends in Specific Population
1.	<ul style="list-style-type: none"> • Integrate infection prevention and control with quality improvement and patient safety measures • Identify opportunities in clinical workflow for prevention • Apply new tools
2.	<ul style="list-style-type: none"> • Formulate targeted tactics • Execute early prevention

The development of efficient infection information systems to reduce HAIs and incidence of ABRIIs has been an emerging issue in the last decade.[1] In 2013, The U.S. DHHS issued “National Action Plan to Prevent Healthcare-Associated Infections: Road Map to Elimination” outlining several major directions for research with an emphasis on a full capacity of health information technology.[12] The report raised concern about a large gap in HAIs prevention because of barriers to using the best available knowledge.

Hospitals as Infection Transmission Systems

Hospitals are infection transmission systems. There are many factors that account for the differences in ABR infection transmission rates among hospitalized subpopulations, such as antibiotic use, infection prevention and control approaches, size of the hospital, and others.[18] The most significant contributing factors include high levels of repetitive contacts to HCPs and a considerable proportion of infected and colonized with ABROs patients.

Contacts between patients and healthcare practitioners (HCPs), among HCPs, and among patients represent the most common routes of transmission of ABR infections. The contaminated hands of HCPs are the most critical transmission route for ABR pathogens. HCPs colonize their hands while providing care to

colonized or infected patients, and can spread the infectious agents among other patients.[19, 20] One study found that nurses can contaminate their hands with 100 to 1,000 Colony-Forming Units (CFU) of *Klebsiella* spp. during clean activities [20], while 10 to 600 CFU/ml can be found on nurses' hands after touching the groins of patients heavily contaminated with *Proteus mirabilis*. [21] The delivery group members, consisting of nurses and nursing aids, are at the highest risk of exposure to infected and colonized patients by being in close and frequent contact with them. Nursing aids or care technicians are particularly a risk group for infection transmission due to their exposure to patients' biological fluids and solids. Research studies provide evidence that the delivery group has a strong impact on the probability of observing a large outbreak, and should be targeted not only for traditional preventive measures, such as hand hygiene, wearing gloves, masks, and gowns, but also new interventions that would restrict frequency and duration of their contacts with patients.[22, 23]

The arrangement of contagious contacts (random mix vs. clusters) among the members of the population and the clustering of contacts are the significant structural properties influencing the spread of infections.[24] When three individuals have a mutual contact, they form a closed triplet or cluster. Anderson reports that "highly connected individuals become infected very early in the course of the epidemic." [25] Szendroi reports that high clustering of contacts means more local spread.[26] Therefore, location and disease distribution are two central elements in epidemiology of infectious diseases in enclosed environments, such as hospitals or long-term care facilities.

Nosocomial infectious agents differ in its abilities to be transmitted to other patients. Most gram-negative bacteria survive on the hands for one hour or more, which makes *the immediate environment* of a colonized patient, such as a ward, a source of infection. One study found that gram-negative bacteria survive on inanimate surfaces longer than on human skin.[27] Gram-negative bacteria can survival on inanimate surfaces, such as brushes, handles, contaminated plain soap, and contaminated antiseptic soap, for many months. *C. difficile* survival on inanimate surfaces can remain for at least 24 hours, but spores can survive for up to five months.[21] The study reported that transmission of *C. difficile* in an endemic setting on a general medical ward affected 21% of patients, with 37% of them suffering from diarrhea.[28] Transmission might be the result of either exposure to direct or indirect sources of infections, such as contaminated surfaces, fluids, aerosols, or exposure to droplets. Many studies brought a body of evidence

showing cases of infection acquisition in the rooms previously occupied by colonized patients.[29, 30] Although the control of HAIs is mostly based on preventive procedures derived from the best available knowledge of potential transmission routes, in some situations the prevention may fail.[31] Thus, a detailed quantification of contacts and exposures in hospital settings can provide some important information for the assessment of both infection transmission risks and infection control measures.

It is critical to develop tools and to enable HCPs, especially those who are at highest risk of exposure to ABR infections, to rapidly detect and communicate these risks in specific populations and make adjustments in real time. Such tools may help to advance tactics and strategies and maximize the benefits of infection prevention and control. Currently, in many hospitals, the current practice is focused on improving the compliance with infection prevention and control. These efforts involve monthly reports on HAI rates, hand hygiene compliance rates, and other applicable metrics. These reports are often retrospective with a substantial time lag due to data acquisition challenges and needs for quantification of the exact measures of HAI rates, based on the complex definitions established by CDC.[32] These measures traditionally serve as a confirmatory evaluation of the effectiveness of infection prevention programs. Their main purpose is to guide policy and disseminate results. At the same time, the exact measures, including surgical site infection rates, urinary catheter-associated infection rates, and bloodstream infection rates, are not practical for communicating daily infection transmission risks and pattern recognition.

1.2. Role of Healthcare Information Technologies in Patient Outcomes

Unintended Effects of Health Information Technologies

A healthcare system's principal goal is to improve the health of populations through the provision of medical services. In the 21st century, the Institute of Medicine (IOM) has placed a major focus on patient safety. The IOM report "*To Err Is Human: Building a Safer Health System*" provided evidence on a strong relationship between patients' outcomes and quality of care.[33] Healthcare quality is defined as the extent to which health service provided to individuals and patient populations improves desired outcomes. In 2005, the Committee on Quality of Health Care in America (CQHCA) emphasized the role of strong

clinical evidence, good communication, and shared decision-making as critical components for providing high-quality healthcare services.[34] CQHCA proposed six quality aims, including safety, effectiveness, patient-centeredness, timeliness, efficiency, and equitability. To achieve these aims, healthcare systems needed data on medical care, cost, and patient outcomes for performance measurements.[35, 36] These efforts necessitated the adoption of health information technologies (IT). Adoption of health IT was incentivized by the provision of the in Health Information Technology for Economic and Clinical Health (HITECH) Act in 2009.[37]

Health IT is broadly defined as the use of communication technology in healthcare to support the delivery of patient care and population care as well as patient self-management. The main intent of HITECH is to improve outcomes on population levels and decrease cost of care. Electronic healthcare record systems (EHRs) provide the potential to address these needs and advance quality improvements by increasing the availability of data. EHRs can capture needed data from multiple sources and generate a vast amount of granular healthcare data.[38] At present, the implementation of EHR has not yet shown significant changes in patient outcomes and cost of care despite of the rapidly accumulating clinical, administrative, and social data. In 2011, McKinney pointed out that publicly accessible quality measures generated from the EHR data reflected only about 10% of the issues affecting quality of care.[39] At the same time, introduction of EHRs have caused a serious undesirable effect on users, such as cognitive complexity.[40] Cognitive complexity relates to activities of identifying, perceiving, reasoning, deciding, comprehending, and planning.[41] The poor data representation has chiefly attributed to users' cognitive complexity.[42-46]

According to Thompson, information-rich specialties, such as aviation, engineering, and healthcare have become overwhelmed by a constant stream of information.[47] Large volumes of data generated in EHRs have made it difficult to find critical data in lengthy, cumbersome to navigate records.[48-50] Scattered and fragmented clinical information causes interruptions in healthcare practitioners' tasks. HCPs very quickly recognized a significant limitation in their ability to process EHR data for decision-making. A similar problem was reported for air traffic control systems.[51, 52] Ineffective data representation in EHRs has created a safety problem by making patients' medical histories look the

same. It became apparent that needed information is not readily available to HCPs while new systems and technologies have attributed to cognitive complexity.

In spite of years of research on human-computer interactions, there is a need for efficient data representation and effective user interfaces in healthcare. New interfaces should allow healthcare practitioners to manage information effectively in order to gain a high level of understanding or clinical sense-making quickly.

Decreasing Cognitive Complexity via Contextualization of Data

There are many ways to solve the problem of cognitive complexity and information overload. In order to decrease cognitive complexities, a system design should support human work. The information should be organized around users' tasks and goals and be presented with minimal demand for cognitive exertion.[51] Few states that "data out of context creates a cognitive challenge while data in context" makes information useful.[53] He criticizes that little progress is made in deriving real value from information and recommends integrating *the context* for the appropriate application of the knowledge.

Abowd and Dey define context as "any information that can be used to characterize the situation of an entity".[54] An entity can be a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application. Contextualization is defined as a "process of adding context to data", and "information is defined as the output of contextualization".[55] Dourish argues that there are two incompatible views of context, a positivist view and a phenomenological view. The positivist theory states that "... context can be described independently of the actions done"[56] while the phenomenological theory claims that context emerges from the activity and cannot be described independently. Faced with challenges in defining context, Sato (2004) proposes to represent context through a pattern of relations among "variables that are outside of the subjects of design manipulation." [57]

Cognitive systems engineering (CSE) uses contextualization for user-centered system design approach to better support human work. User-centered system design integrates the needed information in ways to fit the goals, tasks, and needs of the users. Militello states that "the knowledge of how people think and act in the context of their work-specific environment can inform the design about how to support cognitive functions." [58]

“CSE involves empirical inquiry to understand better how people think in a specific context. CSE does not impose a formal normative theory of how people think or 'should' think. Instead, the study of each work domain involves a process of discovery, wherein errors are considered interesting openings for further inquiry”. [58]

Among several frameworks developed through CSE, a situational awareness-oriented system and interface design (SA) approach focuses on developing information technologies to help people make sense of situations and make better decisions. To design an SA-oriented interface, it is important to determine which data people need to be aware of, how that data needs to be understood relative to operator goals, and what projections need to be made to reach those goals.

1.3. User-Centered Design: Situational Awareness Oriented Approach

Role of Situational Awareness

Endsley and Jones (2012) stated that in complex and dynamic environments, decision making and performance are highly dependent on situation awareness (SA), “a constantly evolving picture of the state of the environment.” [51] They explained that SA incorporates an operator’s understanding of the situation and the meaning of what they perceive in light of their goals. Thus, SA is goal-oriented.

The importance of goals for performance was demonstrated by The Goal Setting Theory, a theory of motivation, which explains what causes some people to perform better in work-related tasks than others. [59] The theory postulated that goals are positively associated with high performance. According to Locke et al. (1997), specific, challenging goals enhance the quality of planning activities, and that planning is positively related to performance. [60] The term goal was defined as “the object or aim of an action”; in a work setting, the goal is defined as “the level of performance to be attained”. In contrast, vague goals were associated with a lower quality planning process and poorer performance. Prominently, goals are translated into strategies suitable to the specific situation.

Many studies in the systems design area have demonstrated that loss of SA can result in poor performance and errors. Endsley (1995) found that 88% of human errors were due to problems with SA. [61] Green et al. (1995) reported that SA requiring an operator to “quickly detect, integrate and interpret data

gathered from the environment” can be impeded with noisy, dispersed, and poorly presented data.[62] Jones and Endsley investigated the sources of the loss of SA in aviation and found that the largest proportion of errors resulted from the failure of the flight crew or air traffic controllers to observe or monitor data. They suggested that better means of displaying the data and improved training in SA strategies can reduce these types of errors.[52] Durso et al. (1998) evaluated causes of the errors identified in two groups of air traffic controllers: those who had SA and those who did not.[63] This study found that some errors related to the inappropriate use of displayed data, poor interpretation, understanding, judgment, reasoning, and planning, which corresponded to other studies’ results.[64] Endsley (1995), Chief Scientist of the U.S. Air Force, concludes that system design should support and enhance users’ SA.[61]

Definitions of Situational Awareness

To better understand the connotation of SA, it is important to review how different investigators defined SA. Many existing definitions of SA have specified different components of SA including the temporal dimension. Sarter and Woods (1991) stated that SA is context dependent while the *temporal* dimension is described as operator dependent.[65] Endsley and Jones (2012) delineated *cognitive* dimensions such as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future.”[51, 61] Smith and Hancock (1995) emphasized the *adaptive nature* of SA: “SA is adaptive, externally directed consciousness that has as its products knowledge about a dynamic task environment and directed action within that environment. Adaptation is the process by which an agent channels its knowledge and behavior to attain goals, tempered by the conditions and constraints imposed by the task environment.”[66]

Bedny and Maister (1999) have also emphasized the adaptive nature of SA in their definition of SA as “the conscious dynamic reflection on the situation”.[67] Several other definitions of SA highlighted the importance of *environmental stimuli*, *informational cues*, *behavioral cues*, *context*, etc. Endsley (1995) pointed out that most definitions of SA neglected the “*situation*” part, a set of environmental conditions that can be characterized by a set of information.[61] The most frequently cited definition of SA in the literature is “being aware of what is happening around you and understanding what that information means to you and in the future” formulated by Endsley.

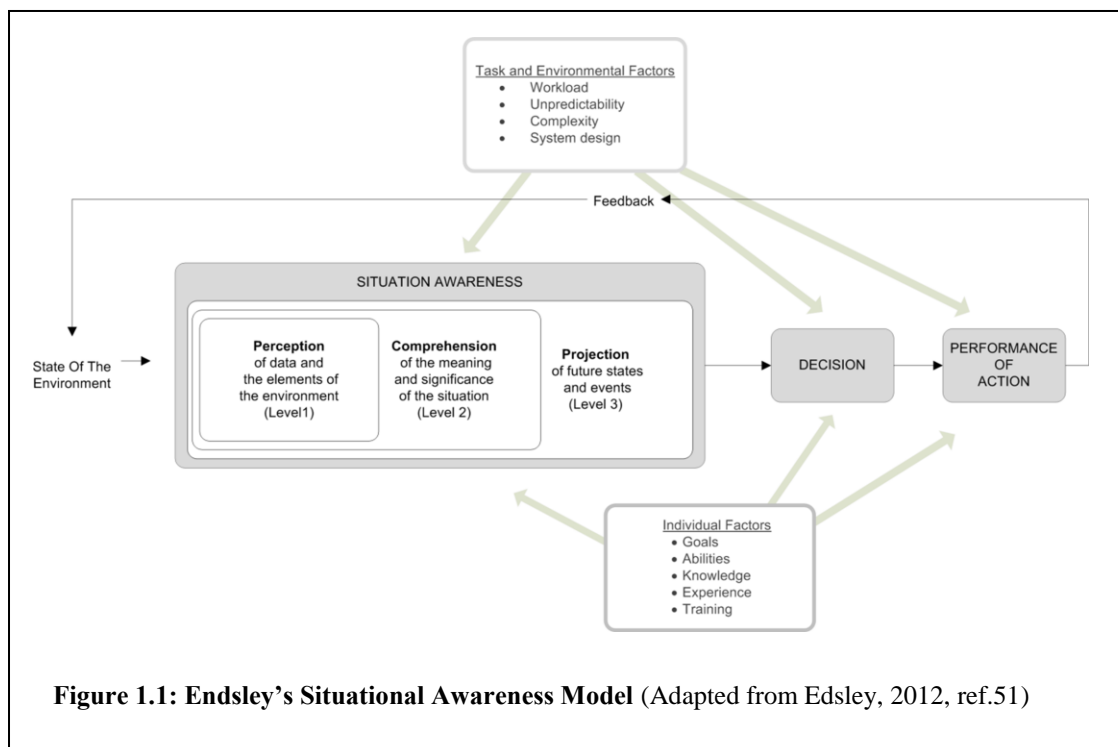
Situational Awareness Theories

SA Theories are grounded into human cognitive functioning and information processing theory. Endsley (1995) refers to research of human physiology showing that the perceptual system has several levels of information processing: at the first level, people detect *signals and target* from an environment by filtering out the noise.[61] At the second level, people organize the signals into meaningful *patterns of information*, which they have to understand by sorting them into *categories* and then integrating them with their existing belief and knowledge networks.

In 1995, Endsley proposed an SA model based on the three essential components, including perception, comprehension, and projection (Figure 1.1). The first level of SA (Level 1 SA) refers to operator's *perception* of the elements in the environment or *raw data* representing the environment regarding to "what elements are present, where they are located, and how fast they are moving".[51] The elements include people, objects, events, and environmental factors. This is the lowest level of SA requiring only confirmation of the status of a particular variable. Endsley informs that "most of the research is focused on this level because it is easiest to investigate and measure". However, Level 1 SA is of minor interest because "if a person lacked an understanding of the patterns and implications, he is not considered to have a good SA".

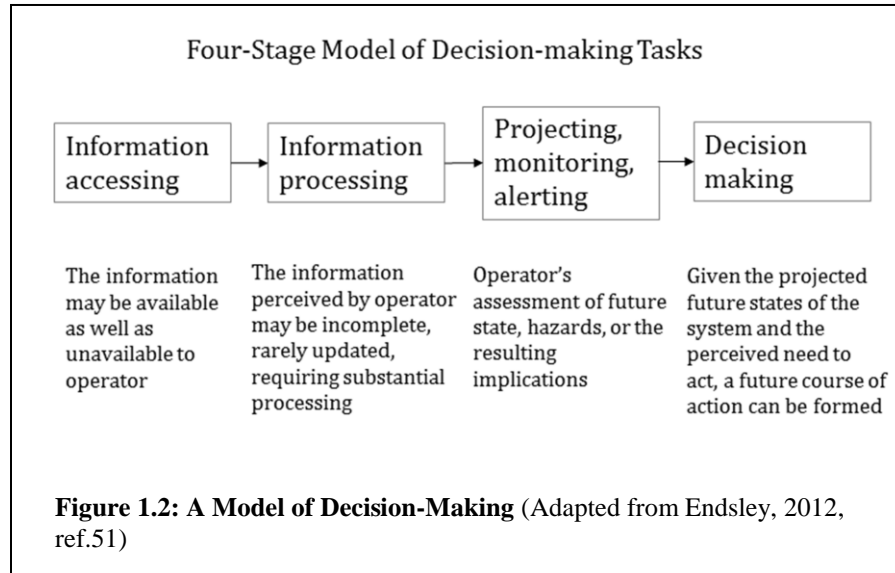
The second level of SA (Level 2 SA) is *comprehension* or *sense making* of the current situation, which requires an individual to *integrate* and *synthesize* diverse data elements. To attain this level, the individual needs contextual data in order to categorize a situation from "a finite set of potential" alternative scenarios. Another important requirement of Level 2 SA is the detection of leverage points in a situation. Leverage points are defined as the opportunities for making dramatic changes in a situation. Sense making is the most critical cognitive operation for understanding the significance of the elements and gaining a picture of what is happening. Endsley states that the degree of comprehension achieved is "a mark of the expertise". Less skilled individuals may exhibit a lower Level 2 SA than their more skilled colleagues. She explains that *comprehension* involves *integrating* external data with knowledge and goals, which in turn "informs the projected status of the world". The challenge for interface and system designers is to identify and represent a context supporting Level 2 SA in the most effective way.

The highest level of SA, Level 3 SA, encompasses “the ability to project the future of the elements in the environment”. Level 3 SA is crucial for personnel, such as air traffic controllers and pilots, performing time-critical activities. They heavily rely on prediction to anticipate problems and deal with them in a timely manner. In healthcare, for example, emergency medicine practitioners have to make decisions rapidly because time plays a significant role in patients’ outcomes. Endsley and Garland (2008) argue that, although there is no threshold of SA that can guarantee a given level of performance, more SA is always better.[68] Higher SA increases the likelihood of effective decision-making and performance.



A decision-making process includes several steps: information accessing, information processing, and projecting (Figure 1.2). Information accessing is an initial step.[51] If the information is unavailable to the operator, SA will be lacking. The first step corresponds to Level 1 SA or perception of information by operator. The second step includes information processing during which the information perceived by operator may be incomplete or rarely updated, requiring substantial processing. This step corresponds to Level 2 SA when operator comprehends the current state of environment. The third step includes

projecting, monitoring, and alerting when operator assesses future state, hazards, and implications. These three steps are the prerequisites for decision-making when operator perceives the need to act.



Situational Awareness-Design Principles

In order to design an SA-oriented system or interface, it is important to develop a clear understanding as to what supporting SA means in a particular domain. This understanding is gained through different methods. Endsley (2012) describes that the ideal SA reflects the analyst's front-end analysis for identification of the information and knowledge formulated with SA in mind. Years of research in SA design have resulted in establishing the SA principles (Table 1.2). These principles will serve as the guidelines for this research study.

Table 1.2: Situational Awareness-Oriented Design Principles

Situational Awareness Design Principles	
1.	Critical cues should be provided to capture attention during critical events
2.	Design should organize information in a manner that is consistent with the person's goals
3.	Design should present data in a manner that makes Level 2 situational awareness (understanding)easier
4.	Global situational awareness is supported by providing an overview of the situation across the goals of the operator
5.	Design should reduce the requirement for people to make calculations

1.4. Situational Awareness in the Healthcare Context

Patient Safety and Disease Surveillance

The SA concept in healthcare relates to the analysis of patient safety and healthcare quality issues in the context of dynamic environment.[69] The systems that enable SA in healthcare and public health are rapidly developing and varying in their applications. Some examples of the state of the art of healthcare SA include Disease Detection and Surveillance, News and Web Trawling, Alerting, Bed Tracking[70], Patient Tracking [71], Incident Command Systems, and EHRs. The major use of SA is observed in emergency management when decision-making and treatments are constrained by time pressure. Timely decisions followed with appropriate interventions and treatments are the key success factors for optimal patient outcomes. For example, a recent Ebola outbreak that occurred in West African countries revealed the importance of the timely communication of an individual's travel history for making decisions to quarantine and adequately prevent the spread of this deadly infection.[72]

Biosurveillance

Many healthcare SA-oriented systems in the U.S. are designed to detect emerging infections and outbreaks. For example, the National Biosurveillance Integration System (NBIS) merges the various sources of information by connecting the surveillance streams and agencies.[69] This system plays a crucial role during the rapidly developing infectious outbreaks because it facilitates timely policy decisions. However, these systems do not communicate the epidemic key characteristics, such as the severity of illness, the disease epidemiology, the transmission characteristics, and the extent of dissemination of the disease in the community, which is essential for effective decision-making. Toner states that such important information has been traditionally determined retrospectively after epidemiological investigations.[69] He doubts that the contemporary systems enable a robust understanding of a rapidly unfolding event, provide an integrated picture, and effectively direct decision makers' actions in a crisis. Healthcare facility data will be important for continuous improvement. Understanding how hospitals and other facilities perform during crises would lead to refinements of the overall hospital emergency preparedness programs.

The primary objective of infection surveillance is to monitor the incidence or prevalence of specific infections, to document their effects in populations, and to characterize affected people and those at

greatest risk. At the community level, surveillance is often an integral part of the delivery of preventive and therapeutic services by health departments.[73] The surveillance systems allow identifying the underlying nature of disease trends (e.g., seasonal oscillations), the length of time for which historical reference data is available (year, quarter, month, week historical data), and the urgency of detecting aberrant trends (e.g., detecting a one day increase). At the hospital level, surveillance is used to monitor HAIs and to detect outbreaks in a hospital. At a hospital unit level, the output of surveillance is used for the timely isolation of colonized and infected patients. To maximize infection prevention benefits in hospitals, decisions on prevention should be based on assessment of infection risks as part of the patient care planning process.[74] It is recommended to document all precautions for infection prevention within the patient's individual plan of care, regularly reassess the risks, and make changes as necessary as the patient's condition progresses. Precautions may need to be modified due to changes in risks during a patient's course of care or patient's needs. For example, patient isolation may have adverse psychological effects on some individuals.[75] Some infection prevention interventions may require re-adjustments due to adverse reaction to them, for example, patient hygienic procedure and healthcare provider hand hygiene with antiseptic solutions can cause skin irritation, dryness, and allergic reactions.[21, 76] Currently, many hospitals use surveillance information to increase the staff awareness about patients with known ABR colonization or infection by flagging them in the EHR. Literature lacks evidence on whether this is sufficient to reinforce the compliance with the evidence-based guidelines or prevent the spread of ABR infections.

Clinical Situational Awareness and Sense-Making

Studies showed that SA-systems have correlated with high individual performance.[51, 59, 77] In healthcare, a few studies provided evidence that SA-systems have been associated with better clinical sense making and patients' outcomes.[78-81] Fine et al. (2007) explored an impact of integrating epidemiological contextual information, derived from public health surveillance data on recent local trends in meningitis epidemiology, into a prediction model differentiating aseptic from bacterial meningitis.[82] After a series of tests, the investigators developed a rule for the epidemiological context adjustor information. This adjustor allowed the correct identification of an additional 47 cases (7%) of aseptic meningitis in 696 children without missing any additional cases of bacterial meningitis. Ball and McElligot (2003) showed that patient recovery in the ICU was attributed to the following contextual factors, geography, the overall

activity level in the unit such as the number of admissions and transfers (activity), the nursing skill mix (permanent vs. agency staff members), and patient dependency status (number of turns required).[83] It appears that SA-oriented technologies may be promising for decreasing HAI rates and promoting cost-effective innovations in infection prevention by enabling HCPs to systematically detect situations where risk of infection transmission and exposure to infections increase, and naturally forcing the healthcare teams to seek better prevention. However, there is a scarcity of literature about contextualization of healthcare data. Bricon-Souf and Newman have categorized the healthcare contextual elements into the following groups: a person by role, location, delivery timing, role reliance, artifact location, artifact state, and medication consumption [84]. While time, location, staff identity, and patient identity are the most common features used for healthcare context representation, activity knowledge is not. There is also a gap in the field of context representation; no recommendations are available about the functional needs of the context. As a result, there is a large gap between fundamental research on context representation and actual context awareness prototypes.[84]

Computerized platforms could effectively mediate coordination of infection prevention and control activities in dynamic hospital settings. New interfaces should allow healthcare practitioners to manage the information effectively in order to gain a high level of understanding quickly. At the same time, in order to avoid the information overload effect, integrating *the context* for the appropriate application of the knowledge is recommended.[53] The challenges for an interface designer include the understanding about type of information that can serve as an actionable context and techniques for representing context that effectively supports Level 2 SA.

1.5. Research Study Objective, Hypothesis, and Aims

There is a need for innovative tools for operational practice to increase healthcare practitioners' SA about situations at high-risk for ABRI transmission. A challenge here is the identification and representation of the information that would effectively facilitate HCPs' SA pertaining to infection transmission risks. The effectiveness of such tools depends on their capability to reduce information-processing requirements and cognitive complexity caused by hospital dynamic environment and large

volumes of granular data in EHR. **The objective** of this original research study was to develop and test a conceptual design of situational awareness-oriented information system for coping with healthcare-associated infection transmission. The research sought to strengthen biosurveillance by optimizing the use of data in EHR systems in a format of actionable real-time knowledge. The key informatics component of this research was solving the problem of information representation.

In this study, the ABR infection transmission situational awareness was defined as a perception of the infection transmission risks (Level 1 SA) and a comprehension of these risks (Level 2 SA) in a context of patient and healthcare practitioner's safety. The goal of a graphical user interface design was to enable healthcare practitioners to promptly gain a high level of understanding about situations at high-risk for infection transmission (Level 2 SA).

It was hypothesized that providing healthcare practitioners (HCP) with a graphical user interface(GUI) visualizing spatial health information on the risks *of exposure to ABROs* would effectively increase HCPs' SA regarding the areas at high-risk for ABR infection transmission, subjects at high-risk of exposure to ABR organisms, and patterns in infection prevention. Increased SA may enhance biosurveillance and result in tactical decisions leading to better patient outcomes. SA is a fundamental concept used to maintain operational safety in high reliability organizations. In healthcare, SA-systems are associated with better patients' outcomes.[78-81] Availability of a common operating picture displayed with the GUI to all stakeholders in healthcare setting(s) may enable HCPs to share their expertise between and within the teams, lead to greater individual and organizational commitment to infection control, and enhance healthcare team's information-seeking behavior aiming at developing tactical decisions and innovative cost-effective strategies.

The Study Aims

Aim #1: To develop a conceptual model for the GUI content aiming at improving situational awareness (Level 2 SA) of antibiotic resistant infection transmission risks and exposures in hospital dynamic environments

Aim #2: To develop the graphical features for empirical information data set, driven by the model's concepts, which would facilitate the user immediate understanding of the common operating picture.

Aim #3: To evaluate the impact of the GUI design on the users' situational awareness by comparing with the situational awareness permitted by the current practice

The study has employed a mixed qualitative-quantitative research method encompassing (1) **conceptualization** of the context; (2) **visualization** of the contextualized data; and (3) **evaluation** of the pilot GUI.

Chapter 2 reviews a behavioral theory to understand factors contributing to organizational performance in a context of SA. The next four chapters describe the three distinct research studies. Chapters 3 and 4 address Aim #1 and represent a knowledge elicitation study for developing the conceptual model. The knowledge is elicited from the published clinical studies on antibiotic-resistant infection epidemiology, infection prevention and control measures, and quality improvement methods. Chapter 5 addresses Aim #2 and describes a case study for constructing the graphical representation of the conceptual model with the use of the Rules for Image Construction. Chapter 6 addresses Aim # 3 and presents a quasi-experimental, pre-post evaluation of the developed GUI conceptual design with the SA self-rating technique.

CHAPTER 2: GOAL SETTING AND TASK PERFORMANCE IN TEAMS

2.1. Introduction

Chapter 2 motivates the research to understand the complexity of healthcare organizations, its dynamic environments, and factors contributing to successful performance. Then, the chapter provides a review of the Goal Setting and Task Performance in Teams Theory and links this theory to the Situational Awareness Theory to understand a relationship between these two theories. At the end, the Chapter includes a picture designed by the investigator that represents a virtual hospital environment and the relationship between the elements of the Behavioral Theory and the Situational Awareness Theory.

2.2. Impact of Hospital Environment on Health Care Performance

Acute care hospitals in the United States are highly labor intensive environments [85] with instant patient flow [86] and fluctuating demands for health services. Iversen et al. (2012) characterize hospital work as mobile, unpredictable, and laborious.[87, 88] Hayes et al. (2011) describes that the work in hospitals is performed by a highly heterogeneous group of people with disparate goals and working styles, who must come together with one overarching goal: high quality patient care.[89] Inherently, the organization of these distributed services is complicated by the specialization of medical services and its spatial organization, which often leads to delays of services and waste of resources.

Distributed services require a rigorous coordination of the providers and resources based on the demands for specific services. Ohboshi emphasizes the need to enable HCPs to revise and change the other HCPs' workflow when it is necessary.[90] Hendrich et al. report that hospital nurses spent, on average, 86 minutes per 10-hour shift on care coordination [91]. Tucker adds that nurses spend approximately 44 minutes per 8-hour shift to coordinate the resolution of the failed activities.[92] Bricon-Souf et al. explain that time constraints and urgency of care complicate the care coordination.[93] These dynamic environments cause uncertainty for adequate planning of services and create conditions where some "low-

priority” tasks may be traded off for emergent care. The efficient coordination of care requires the anticipation of the demands and planning of healthcare services.

The other critical challenges for organizing healthcare services include a failure to translate and implement new evidence into practice across multiple contexts.[94] Rangachary reports that many hospitals have difficulty consistently implementing evidence-based practices (EBPs) at the unit level, a problem known as “change implementation failure”.[95] Some estimates indicate that two-thirds of organizations' efforts to implement change fail.[96] Ferlie and Shoetell (2001) state that barriers to implementation may arise at multiple levels of health care delivery: the patient level, the provider, team or group level, the organizational level, or the policy level.[97] The successful implementation of an intervention is judged by the degree to which a desired level of performance is achieved.

For example, the Consolidated Framework for Implementation Research (CFIR)” lists five major domains for identifying potential influences on intervention implementation: (1) intervention characteristics, (2) the process of implementation, (3) external context (economic, political, and social context), (4) internal context (structural characteristics, networks, available resources), and (5) characteristics of the individuals involved. CFIR recognized that a new intervention needs to be evaluated for compatibility, adaptability, complexity, and cost.[96] For successful implementation of any intervention, planning and evaluating are critical. According to Mendel et al. (2008), the fundamental objective of planning is to design a course of actions to promote effective implementation by building local capacity for using the intervention.[98] For successful implementation, the implementers assess stakeholders' needs, strategies to be adapted for appropriate subgroups, strategies that help simplify execution, and methods for tracking progress toward goals.

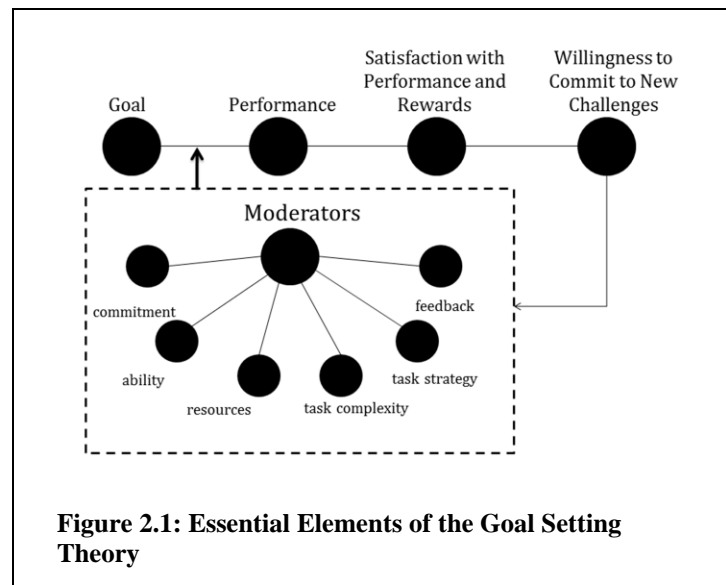
The Practical Robust Implementation and Sustainability Model (PRISM) explains organizational characteristics that successfully change behaviors in a given clinical area, including people, infrastructures, monitoring, and feedback.[99] PRISM considers these characteristics at three organizational levels: (1) top management, (2) middle managers, and (3) front-line teams. In addition, PRISM emphasizes patient engagement [100, 101] and the use of technology [99] as the essential components in the model.

Plsek and Wilson, the internationally recognized experts on innovation in complex organizations, criticized the current management approach in healthcare, based on utilization of detailed plans, guidelines, and standards and recommended a method of “minimum specifications” to create an environment where innovations and complex behaviors can emerge.[102] Instead, a positive dimension of variation was accentuated. According to Plsek and Wilson, a “minimum specification” approach would allow staff to learn how variations in structure and process contribute to variations in outcomes. They believe that the current approach fails to address some unpredictable events, while managing healthcare organizations as a whole system and relationships between parts of the system is a better approach. One example may serve as an illustration of managing healthcare organizations as “individual parts” rather than “whole system”: hospitals often measure HAI incidence rates, a number of specified infections per 100 patient-days, based on a list of specific inclusion and exclusion criteria. Such measurements, representing a small subgroup of patients, are not suitable for daily management and resource planning. From management perspective, knowledge about daily prevalence of infected patients would be more useful for planning of daily activities and resource allocation. Healthcare technologies may facilitate the “whole system approach” and enable discovery of variations in demands and processes by abstracting, computing, and visualizing needed data.

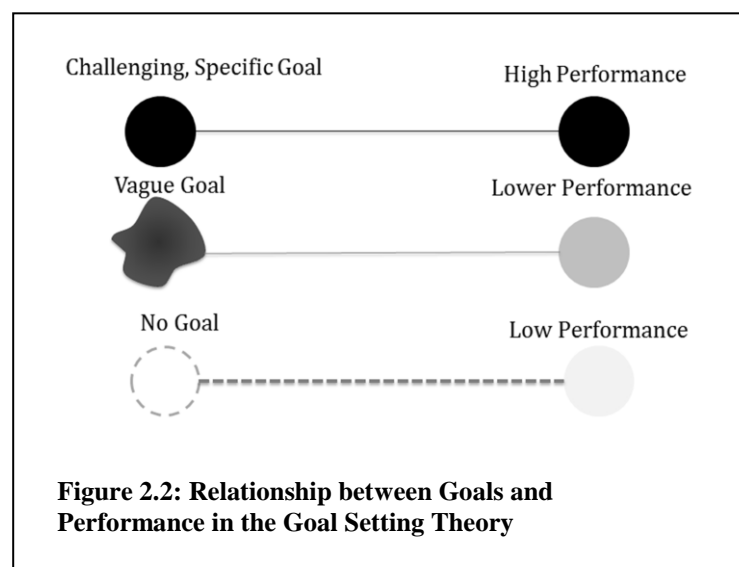
Specifics of healthcare environment necessitate a review of organization behavioral theories to better understand the role of the SA approach for interface design in addressing the organizational healthcare needs. Behavioral theories provide systematic knowledge on performance improvement by explaining the logic about an underlying relationship between goal and performance relationship. These theories explain a role of performance mediators, such as feedback, task complexity, and task strategies. Understanding these theories can provide insight about compliance with infection prevention and control practices from a perspective of macro-context or a whole system.

2.3. The Goal Setting and Task Performance Theory Findings

The Goal Setting and Task Performance in Teams Theory was developed by Locke and Latham.[59] The main argument of this theory is the existence of internal individual motives, such as the need for achievement. Locke and Latham postulated that the attainment of high performance leads to individual satisfaction and commitments to new challenges (Figure 2.1).



The Goal Setting Theory explains what causes some people to perform better in work-related tasks than others. The main findings from The Goal Setting and Task Performance research are: (1) a specific, high goal leads to higher performance than no goal or vague goal (Figure 2.2); (2) the difficulty level of a goal has a linear relationship with job performance; and (3) performance feedback has indirect effect on performance, only when it leads to the setting of a specific, high goal.



The first and most critical postulate is that goals predict performance. The term “goal” is defined as the object of the aim of the action. In a work setting, the goal is defined as the level of performance to be attained.[59, 103] Setting specific, challenging goals leads to higher performance. Goal setting theory states that the mechanisms of this relationship are fourfold: (1) a specific, high goal orients an individual’s attention and efforts toward goal-relevant activities; (2) once an individual chooses a goal and chooses to act on it, effort is mobilized and expanded in proportion to the difficulty level of the goal; (3) specific, high goal prompts an individual to draw upon the accessible knowledge, skills, and task strategy required to attain it. Goals play a significant role in regulating human action at both micro and macro levels. Goals have positive and negative effects on a person. If a person experienced greater success in goal attainment, this person develops a greater degree of satisfaction. Similarly, if a person cannot attain a goal, he can experience dissatisfaction. Goal setting also increases interest and reduces boredom with a routine, repetitive task. Without the necessary resources, the goal is unlikely to be attained.[104] Locke and Latham demonstrated that goals serve as a benchmark against which performance feedback can be evaluated.

The theory of goal setting was developed inductively from experimental and correlational design studies involving almost 40,000 participants in eight countries performing 88 different tasks in laboratory and field settings to examine the effect of a goal on the performance in 1990. Locke and Latham communicated that “there is strong evidence that the increases in job performance produced by goal setting have important economic and practical value. The gains in dollar value of output as sold are substantial under typical real-world conditions. The percentage increase in output is also substantial, and for organizations, this increase makes it possible to achieve important decreases in labor costs.”[59] The overall validity of this theory and its practicality in the workplace was assessed by multiple reviews, meta-analyses, and competitive analyses of goal setting.

It is important to acknowledge the opposite theories, so-called reductionist theories, which existed in the 1950s and 1960s. Behaviorists who believed in “punishments” and “reinforcements” promoted these theories. The term “reductionist” described the main argument of these theories meaning that discrepancy reduction is the primary source of motivation. The Control Theory is an example of reductionist theory and has its root in electromechanical engineering, which describes how torpedoes and thermostats work.[105] The Control Theory postulates that there should be a standard for the object to meet, electrical or

mechanical feedback, a detector to spot discrepancies between the standard and the current state of the object, and an effector to take corrective action. Locke and Latham (2013) criticize these theories by pointing at problems with applying an engineering model to human beings and argue that if discrepancy reduction alone is the primary source of motivation, people "would simply abolish their goals whenever possible". According to Bandura and Locke (2003), people volitionally create discrepancies between their current performance and a specific desired goal where discrepancy reduction is simply a correlate of goal-directed action.[106] Discrepancy production, or setting a goal for something an individual desires, is the second correlate, which is the source of motivation.[59] It appears that the Goal Setting Theory provides an insightful framework for improving quality and performance in healthcare.

2.4. Goal-Performance Relationship at Individual Level: Micro Goals

The Goal Theory hypothesizes that at an individual level, the goal-performance linear relationship is moderated by ability, feedback, commitment, task complexity, and situational restraints. These moderators can enhance or weaken this relationship.

Performance Feedback

The term "feedback" is often used in different scientific fields ranging from biological systems to non-living systems. In social science, feedback is one of the most important moderators of the goal-performance relationship. It regulates performance by allowing people to decide if more effort or a different strategy is needed to attain their goal(s). When feedback on performance is not available, goal setting is ineffective for increasing performance. When feedback on performance is available but ignored, the performance also does not improve; a subject did not set a new goal and failed to translate the feedback into action.[107]

Ashford and Cummings defined feedback as "information that tells a performer how well he or she is performing a task or progressing with respect to a goal".[108] According to Locke and Latham (1990), feedback stimulates individuals to set subsequent goals for their performance.[109] Performance improves when both feedback and goals are present. Feedback is characterized by frequency, source, specificity, object of feedback (process, outcome), type of influence on a subject, confidentiality mode and

others. Feedback can be nominal or comparative. The purpose of nominal feedback is to inform about changes in the environment while comparative feedback is to inform about the gaps in the expected and observed performance.

Frequency of feedback may have an effect on performance. If the feedback is rare, employees do not have timely information. If the feedback is very frequent, it can be redundant, time-consuming, and distracting. Frequency of feedback is dictated by the nature of the goal that is pursued, by the organizational context, or by an industry context. For example, in a fast-changing industry, such as aviation, emergency care, or military operations, more frequent feedback may be seen as critical and appropriate.[59] The rate of environmental changes may determine the rapidity with which decisions should be made.[109] For example, a healthcare team experiences a spike in demand for infection prevention services when a number of infected patients admitted to hospital rapidly increases due to an outbreak in a community. Under these circumstances, the rapidity of decision-making must increase in order to effectively coordinate infection prevention services and respond in a timely manner. The frequency of feedback needs to increase to address these needs.

Cianci, Klein, and Seijts (2010) recognized that feedback also has affective consequences because people felt joy or disappointment based, in part, on feedback regarding their success or failure to attain a goal.[110] Locke and Latham communicated earlier a need to study the interactive effects of goals and feedback on subjects. Feedback's affective consequences are important because it can suggest that feedback can be used as a reward for people. There are other nuances of feedback related to emotions. For example, group feedback and goals serve as an accelerator of those positive or negative effects. Specifically, "emotional contagion processes" amplify the effect of group feedback or goals as emotions experienced by one or another group member spread throughout the group consequences.[110] "Negative" feedback can also result in positive affect and increased goal setting only when the discrepancy between performance and goal is reasonably small.

De Stobbeleir et al. (2011) also recommended examining the source of feedback.[111] Healthcare systems utilize feedback with various modes of delivery, frequency, and purpose, including alert and flagging systems, compliance reports, and monitoring dashboards. The new directions for research on other

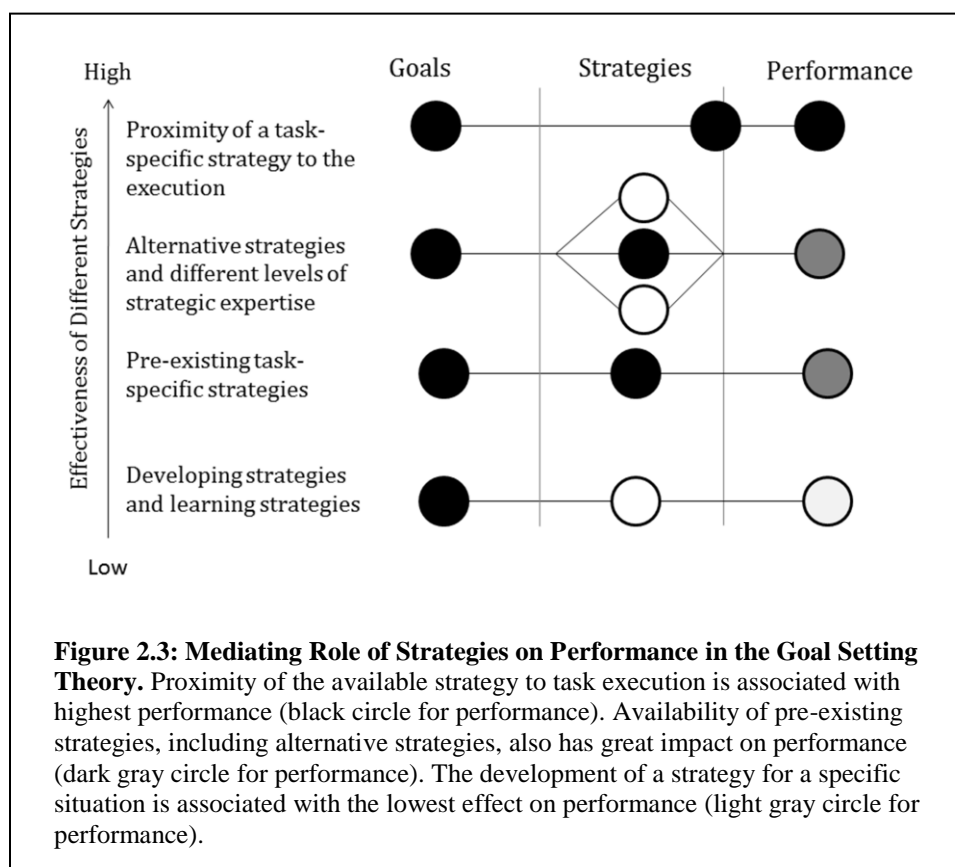
nuances of feedback focus on whether feedback is on process vs. outcomes of performance, whether it is given or sought, and whether it is given verbally or through a graphic objective presentation or virtually. For example, infection surveillance is a feedback system on patient infectious outcomes. Infection surveillance aims at informing healthcare teams to undertake timely, appropriate infection prevention and control measures. Overall, performance improves when both feedback and goals are present.

Strategies

The term strategy refers to a plan or pattern of decision-making, or actions designed or undertaken to achieve a goal. Locke et al. argued that strategy has an indirect effect on goal-performance relationship. While strategies enhance performance, goals motivate strategy development, which represents a cognitive process (Figure 2.3).[112] Strategies can be categorized into four categories: three categories are focused on the task (task strategies), and one category is focused on the individual's self-regulation. The task strategies include: (1) task-specific strategies, (2) strategy development, and (3) search and information processing.[59]

1. Task-specific strategies refer to knowledge that is applied directly to judgments and actions on a specific task being performed. Operationalization of task-specific strategies include measures of the repeated use of a strategy that had worked in the past [113] and the degree to which participants followed a prescribed strategy for the task.
2. Strategy development is devoted to the development or refinement of task-specific strategies during performance of the task.
3. Search and information processing strategies (SIPs) include measures of the actual cognitive processes that can lead to strategy development, such as hypothesis testing and critical thinking, as distinct from those that relied on self-reports of effort devoted to development of a specific task strategy. Search and information processing are most likely to occur when a task is novel or challenging for the individual or dynamically complex, such that existing strategies must be adapted or new ones developed to achieve a goal.[114]
4. Self-regulatory strategies include all strategies that are focused on the personal allocation of effort plus the management of emotions and self-evaluative reactions to the task.

All four types of strategies have a positive effect on performance, but the magnitude of that effect varies as a function of the proximity of the strategy content to the actual execution of task behaviors. Task-specific strategies that are based on pre-existing, task-relevant knowledge from long-term memory have the greatest impact on task performance ($r = .302, p < .001$), followed by strategies requiring testing, refinement, and development of task-specific strategies ($r = .237, p < .001$). Strategies requiring search and information processing have the least effect on performance ($r = .095, p < .001$). Self-regulation strategies also have a strong positive effect on performance ($r = .233, p < .001$). Wood and Locke (1990) suggest that the self-regulation and more task-specific strategies may have additive effects on performance for selected tasks.[115]



Some models treat strategies as a mediator between goals and performance. The mediator argument is that goals activate the application of or search for strategies as part of an individual's goal-striving efforts. Although goals simulate the application of strategies, they do not guarantee that a person

will apply or discover the correct strategy. Latham and Locke postulated that the effectiveness of strategies simulated by goals will depend on prior knowledge of the task for the application of strategies and of meta-search strategies, such as hypothesis testing, for the discovery of new strategies.[116]

Other models treat strategies as pre-existing knowledge that can be used to achieve a goal.[117] The moderator argument is that goals will have a greater impact on performance for individuals who have knowledge or strategies for performing the task than for individuals who either lack the knowledge or adopt faulty strategies. A conclusion from this argument is that more experienced individuals or experts, who will have more task-specific strategies available, will experience greater performance gains due to the focusing and persistence effects of goals than novices or non-experts. Overall, specific, challenging goals remain strong and general predictors of individual performance when strategies are taken into account.

2.5. Goal-Performance Relationship at Organizational Level

According to PRISM, a healthcare organization is framed in an external context, divided into macro context (e.g., external and internal organizational policies, demands for services, market share, etc.) and a micro context (e.g., suppliers, providers, patients, patients' families, and others). Locke and Latham's Theory of Goal Setting (1990) postulated that at the macro-level, the different parts of the organization's environment could vary in uncertainty. Environmental uncertainty can affect performance because goal setting in a highly uncertain environment is problematic; in an uncertain environment, the information required to set goals may be unavailable.[109]

Healthcare organizations and people perform complex tasks in uncertain, unpredictable environments where they have to pursue multiple goals and multiple goal alternatives simultaneously. This may lead to goal conflict when people have to do more than one thing at the same time but cannot merge different goals due to resource limitations. For example, an experiment by Schmidt, Kleinbeck, and Brockman (1984) showed the effects of working on a dual task on performance.[118] The results showed that when participants were given a goal to improve their tracking performance, their reaction time decreased. When participants were assigned a goal to improve their reaction time, their tracking errors increased. Schmidt et al. stated that performance was proportional to goal difficulty level. This experience

generated several hypotheses. One hypothesis states that a decrease in performance is caused by limited attentional resources or due to time constraints. Another hypothesis is that in a two-goal environment, one goal may be more “aversive and attractive” than another goal.

Locke and Latham (1990) hypothesized that multiple goals are independent of each other and require trade-offs for resources that are limited in nature, such as attention, time, money, people, and physical resources. Several researchers discussed that, at the macro level, multiple goals require significant information-processing requirements, which is beyond the capability of individuals.[119-121] Kernan and Lord (1990) suggested that priority management is the central question “faced when confronted with multiple-goal pursuit that hinges on limited resources”. [122] Locke and Latham (1990) hypothesize that people can “prioritize goals and behave accordingly within the limits of their cognitive capacity and ability”. [109]

Several research studies have characterized the currently practiced infection control interventions as prominently time-consuming activities viewed as barriers for clinical work itself.[123-125] Low adherence to infection prevention and control measures by HCPs can be explained by their perception of the infection prevention activities as “low priority” if they face an emergency and have to prioritize their tasks. Such perception may be based on the difficulties to connect the episodic breaches in infection control measures to adverse patient’s outcome. Sometimes, even the systematic breaches in infection control may not lead to a specific infection outbreak due to different infection incubation periods, patient’s immune defense status, and a concentration of the “digested” pathogen. The infection prevention and control activities potentially have to compete with other clinical tasks for limited resources, such as time, attention, and staff.

Goals serve a unifying function by mobilizing and directing organization members’ efforts toward a common end. The hypothesis communicated by Locke and Latham is that specific goals would lead to a more rational planning process resulting in detailed and comprehensive strategies. By documenting such strategies, organizations create extensive contingency plans. Goals can enhance the quality of an organization’s planning activities, and that planning is positively related to performance. In contrast, vague goals were associated with a lower-quality planning process and poorer performance. Locke and Latham

(1990) postulated that the increase in environmental uncertainty will require increasing the number of specific goals, different types of feedback, and decreasing the time horizon for feedback.[109]

In order for macro goals to influence performance, it may be necessary that the goals be translated into strategies suitable to the specific situation. However, Locke and Latham (2012) suggested that one would expect that as uncertainty increases, it would become increasingly difficult to develop specific long-term goals and plans. They postulated that setting proximal goals and providing proximal feedback might be an important mechanism by which organizations can reduce uncertainty. “Proximal feedback regarding errors (error management) can yield information for people about whether their perception of reality is aligned with what is required to attain their goals”.[59] Further, they pointed out that in dynamic situations, it is particularly important to actively search for feedback and react to it quickly to attain the goal.

DeShon et al. (2004) developed a multi-level, multiple goal model of individual and team regulatory processes.[126] Their research showed that when individuals received individual-level feedback, they set the highest goals, which is important for performance, in comparison with those who received a combination of individual and team feedback. When individuals received only team feedback, their goals were lowest in comparison with the previous two types of feedback. Several investigators demonstrated that feedback could make certain tasks and goals salient and affect individuals’ attention and efforts more effectively.[127, 128] Northcraft et al. (2011) study also found that more frequent and specific feedback for a given task led to higher performance.[127] Another study also explored how characteristics of the feedback impact the allocation of resources (time and effort) among competing tasks.[129] It was found that individuals had better performance when they were provided with a higher quality feedback. The higher quality was expressed as timelier and more specific feedback. It was explained that resources allocated to tasks mediated this effect: individuals invested more resources when they received timely and specific feedback.

Locke and Latham concluded that dynamic environments could create uncertainty for adequate planning, obscure execution, and lead to low performance. The rate of environmental changes may determine the rapidity with which decisions should be made. Anticipation of the future and preparation for it in terms of defining specific goals and correct strategies can lead to better performance and adherence.

Anticipation and planning can be more effective if a decision support system utilizes data on the historical environmental changes and performance to inform the front-line staff and management about progress toward the goals; it could also prescribe specific actions to enable proactive management.

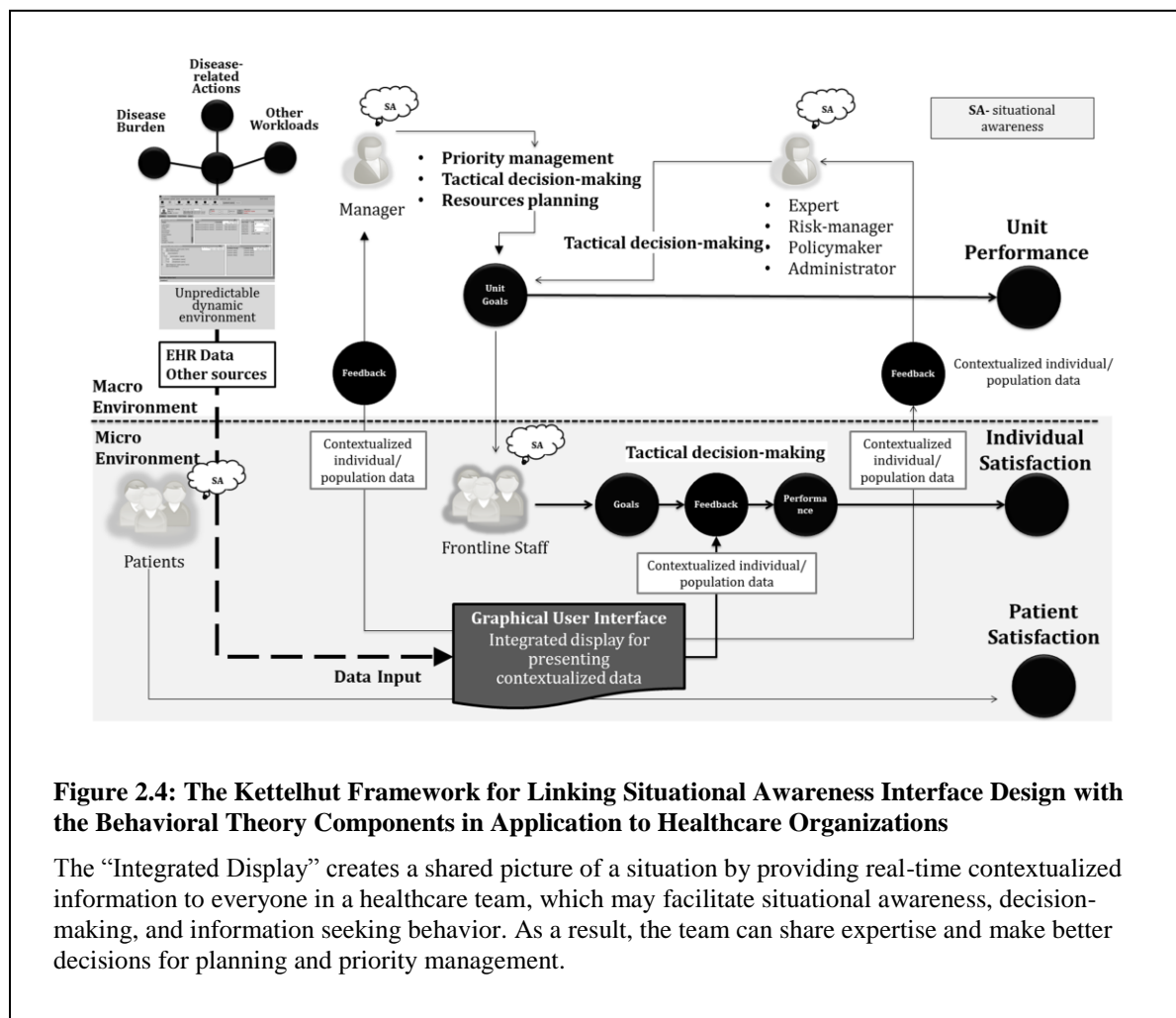
2.6. Linking Behavioral Theory and Situational Awareness-Oriented Interface Design

Figure 2.4 depicts macro vs. micro levels of a hospital. A macro-level represents a unit-level overseen by middle managers and experts, while micro-level represents an individual level (e.g. bedside staff, patients, etc.). The hospital staff operates as a distributed team where a policy-making group of practitioners and experts, who adopt new guidelines (strategies) is operationally disconnected from the front-line delivery group. Such distributed services require a rigorous coordination. There is a need to help HCPs to translate macro goals into strategies suitable to a specific situation by utilizing the information on variation.

Key Points

- The rate of environmental changes may determine the rapidity with which decisions should be made.[109] An SA-design should provide nominal feedback on environmental changes (e.g., disease burden) and comparative feedback on the gaps in the observed performance (e.g., infection control activity) because environmental uncertainty may affect performance of a front-line team.
 - The nominal feedback (disease burden) would enable users to: (1) assess the demand for different services, (2) prioritize goals, (3) develop strategies, (4) detect unpredictable events, and (5) enable adequate planning by monitoring the aberrations in disease burden.
 - A combination of these two types of feedback may reduce the staff information-processing requirements and facilitate a more rational planning process resulting, for instance, in early infection prevention.
- More frequent and specific feedback for a given task (e.g., infection control activities) should lead to higher performance. An SA-interface design can provide real-time feedback to facilitate individuals' SA and priority management. Then, individuals would invest more resources when they receive timely

- and specific feedback. As a result, the individual as well as unit performance would improve, and satisfaction with the results will be achieved.
- The SA-interface can “act” as a platform representing the local environment or situations to support team’s SA and strategy development.
 - In dynamic situations, it is particularly important to actively search for feedback and react quickly to it to attain the goal. The SA-interface could facilitate anticipation and planning by presenting data on the historical environmental changes and on team and individual performance.



Based on the appreciation that hospitals are complex adaptive systems with dynamic, unpredictable, and laborious environments requiring considerable information processing, the data on infection prevention and control activities need to be integrated with the data on the environmental changes to provide the necessary comprehensive information for planning of healthcare services, setting specific goals, and developing strategies in a timely manner.

2.7. Summary

Chapter 2 summarizes how goals, specific feedback, and strategies can mitigate uncertainty and complexity of healthcare environment in an SA-oriented interface. The next two chapters describe a process of developing an infection transmission SA-oriented conceptual model as groundwork for designing an ABR infection transmission SA GUI.

CHAPTER 3: DEVELOPING THE RESISTANT INFECTION TRANSMISSION SITUATIONAL AWARENESS CONCEPTUAL MODEL

3.1. Introduction

Chapter 3 and Chapter 4 address Aim #1 To develop a conceptual model for the GUI content aiming at improving situational awareness (Level 2 SA) of antibiotic resistant infection transmission risks and exposures in hospital dynamic environments. Chapter 3 presents a knowledge elicitation study, outlines the goal and the research questions necessary for addressing Aim #1, and provides the literature review on epidemiology of ABR infections and essential infection transmission risk factors. Chapter 3 includes a discussion on the development of an epidemiological context for the ABRITSA conceptual model. The risk factors, derived from the literature, are considered then in the light of the Situation Awareness-Oriented design principles and the essential concepts of the Theory of Goal Setting, such as feedback and environmental uncertainty. Chapter 3 eventually summarizes the identified ABR infection transmission concepts, constituting the epidemiological context of the ABRITSA conceptual model.

3.2. Study Objective, Design and Methods

The objectives of this study are: (1) to develop an antibiotic resistant infection transmission situational awareness conceptual model grounded in the context of epidemiology of nosocomial pathogens and quality measurements and (2) to examine the study EHR data for the model's chief concepts. To address these objectives, the study needs to answer the following research questions:

Research Question 1: What information can serve as an antibiotic resistant infection transmission (ABRIT) context?

Research Question 2: What EHR data can be utilized for the model's concepts?

This is a knowledge elicitation study based on the modern epidemiology literature review and the examination of the study EHR data. The expected primary outcome is the development of the ABRITSA

conceptual model. The study received the University of Nebraska Medical Center Institutional Research Board (IRB) approval to access the EHR patient data (IRB #: 436-14-EP).

The study setting is a 50-bed medical-surgical unit at a Midwest teaching hospital. The unit patient population consists of approximately 45% of solid organ transplant patients (45%), 20% of cancer patients, 20% of internal medicine patients, and 15% of general surgery patients.

3.3. Developing Critical Cues Depicting Nosocomial Infections Epidemiological Context

The study conceptual model should provide users with critical cues depicting epidemiological circumstances of an enclosed environment at a given time. These critical cues should focus on ABR infection transmission risks. Nosocomial infection epidemiology knowledge provides a foundation for identifying infection transmission risk factors or cues. In this study, the cues are defined as signals enabling the users to understand the prevalence and distribution of the risk factors in a specific population on demand.

This knowledge about ABR infection transmission risk factors has been derived from epidemiological observations, investigations, and modeling. Epidemiologic modeling helps investigators to better understand the spread of infections, to compare effects of different diseases in different populations and at various times, to compare the effectiveness of infection prevention or control procedures, and to develop new policies.[73] Epidemiologists use mathematical modeling to identify methods of infection prevention and control. These models can also predict the movement of infection through populations over time. Re-utilizing the knowledge developed with epidemiologic models is a reasonable approach for a GUI designer.

Ethical issues related to infections make it impossible or expensive to run experiments in humans. Data used in studying the spread of infections is available from naturally occurring epidemics or endemic diseases; however, it is often incomplete and lacks reliability. For example, onset of an infection or exposure to an infectious agent is often unknown. Incomplete data precludes the researchers from making accurate and precise parameter estimation.[73] Consequently, policy makers and researchers often use

surrogate measures of the spread of infections and infection burden in their assessments. As a result, the GUI designer will have to consider these issues and evaluate the impact of the design on different healthcare stakeholders to recognize possible design limitations.

Patient Infectious States (Phenotypes)

Rothman has classified the outcomes of infections on two separate axes: the progression axis and the transmission axis. The transmission axis includes the events related to individual's exposure to infection, transmission of infection between individuals, and implications for health among those affected by transmission from the infected person. This axis directly links to public health and safety while the progression axis deals with medical care. The transmission axis categorizes the members of a population into one of the following transmission-related states: "susceptible", "infectious", and "recovered and immune".[73] The emergence of ABROs has led to an additional state named colonization with ABROs, which has an important distinction from the infection state.

Antibiotic resistance, which is a major genetic characteristic of an infectious agent, has a profound effect on the ability to treat infections successfully. It may alter the course of an infectious process by extending the duration and severity of an infectious disease. **Infection** caused by ABRO is defined as a serious illness when ABRO contaminates wounds, the bloodstream, or other tissues. In contrast, **colonization** with ABRO may occur in the gut, nasal cavities, skin, or other body surfaces without causing symptoms. Individuals with asymptomatic colonization are often called carriers. They increase the risk of infection acquisition by the other members of the population because the carriers can introduce ABROs into the environment for years.[130-133] Thus, it is critical to communicate the information on colonization with ABRO in order to effectively prevent the spread of these pathogens in the population. However, it is important to acknowledge that patients may represent a variety of clinical infection situations when they are observed in a cross-sectional view.

The HCPs use the terms "colonized" and "infected" in patients with ABROs inter-changeably, depending on patients' course of disease. For example, patients with ABRO may be (1) asymptotically colonized with ABRO and receive antibacterial therapy for an infection caused by any organism; (2) they may have an infection caused by the ABRO(s) without a prior history of colonization; (3) patients may

have a history of ABR infection with one organism and experience an infection with a new ABRO.[8, 134] Some patients can be colonized with only one ABRO that is resistant to a series of different antimicrobials or more than one ABRO with resistance to many or even all available antimicrobials.[135] The HCPs use the term “infected” or infectious in the patients with active infections, which can be represented with both ABRO(s) and non-ABRO(s). Patients can acquire different infectious agents simultaneously (poly-infection) or sequentially (super-infection) or can become re-infected with the same agent (recurrence) as a result of ineffective treatment or a new acquisition.[136-139]

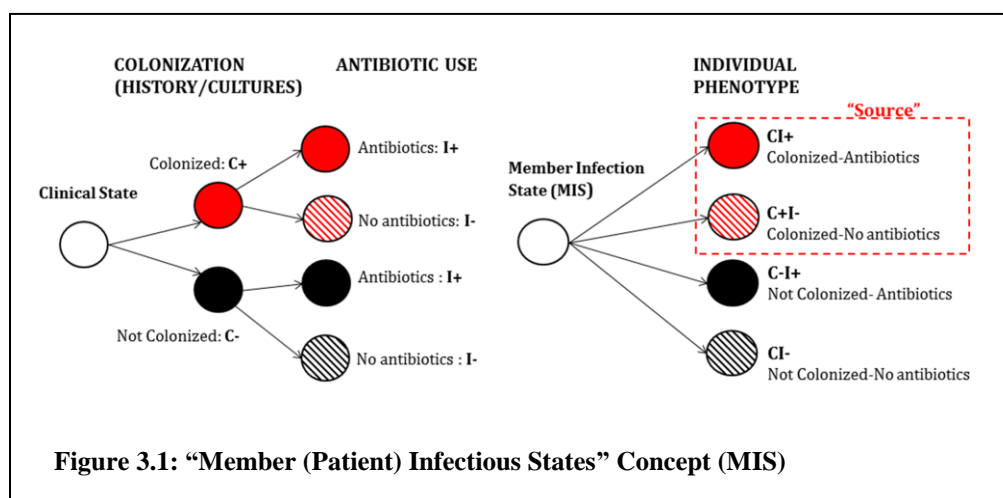
The rationale for separating the two concepts, “Colonized” and “Infected”, is derived from a practical perspective. Literature provides evidence that colonization is often persistent, and once the patient becomes colonized, he remains colonized for a very long period.[130-133] Hospitals flag these patients for isolation to reduce the risk of the infection spread to other patients. For example, the information about patient’s colonization history, regardless of the onset or time of colonization, informs front-line healthcare practitioners about the need to practice certain infection control measures. On the other hand, the information about patient’s receipt of antibacterial therapy informs antibiotic stewardship specialists about a risk of developing a new ABR infection or re-activating the earlier ABR infection in a patient.[140-143] Patients receive antibiotics as prophylaxis of infection prior, during, and after an invasive procedure.[144] In some immunocompromised patients, for example cancer and transplant patients, antibacterial prophylaxis can be prolonged. More commonly, patients receive antibiotics as a treatment of an infection caused by bacteria. Less frequently, patients receive antibiotics for an infection caused by viruses, which is considered a poor practice.

Application

If an individual is in a hospital setting, he or she is at risk of infection. Therefore, the first concept in the model “**Member**” is defined as any individual who is at risk of infection. Second, because the infection can be caused by ABRO(s) and/or non-ABRO(s), there should be a criterion classifying patients into “carrier” of ABRO vs. “non-carrier” of ABRO. All carriers of ABRO, regardless whether they have asymptomatic colonization s or active infection caused by ABRO(s), can be labeled “**Colonized**” “**C+**”. The non-carriers of ABRO can be labeled “**C-**” or non-colonized. In this study, the criterion for classifying

a member as “Colonized” is determined by his *clinical cultures from the specimens with ABR isolates* identified and/or a history of colonization. Each patient who receives antibiotics can be labeled “**Infected**” or “**I+**”. Those patients who do not receive antibiotics are considered as non-infected or “**I-**”. In this study, the criterion for classifying a member as “Infected” is determined by *receipt of intra-venous (IV) antibiotic* regardless of the ethiology of infection.

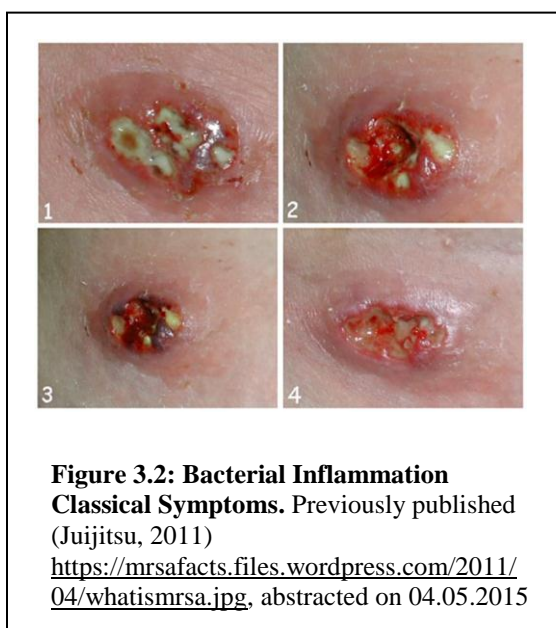
The “Colonized” and “Infected” concepts have binary outcomes “Yes” and “No” to describe patient status. Based on the discussion above, there can be four possible situations: (1) colonized patient who receives antibiotics (CI+), (2) colonized patient who does not receive antibiotics (C+I-), (3) not colonized patient who receives antibiotics (C-I+), and (4) not colonized patient who does not receive antibiotics (CI-) (Figure 3.1). The new concept “**Member Infection State**” (MIS) should classify each member of a population into one of these states. In this study, the following short abbreviations will be used throughout the research: (1) “CI+”, (2) “C+I-”, (3) “C-I+”, and (4) “CI-”. The “CI+” and “C+I-” members comprise a group conceptualized as “**Source**” of ABROs (Figure 3.1).



The information about MIS may support Level 1 SA and Level 2 SA in HCPs. Computer platforms can make this information explicit to all HCPs, prompting a quick comprehension of each patient infection state. The patient information can be de-identified for sharing the information for public health (e.g. occupational hazard assessment). Real time feedback on patients’ infection states may improve

comprehension about the demand for infection prevention activities. Visualizing patient's infection states, such as CI+, C+I-, C-I+, and CI- may improve Level 1 and Level 2 SA in HCPs about the disease distribution and risk of infection transmission in real time.

As communicated in Chapter 2, feedback has an affective property related to emotions. Literature lacks information about how different user graphical features of health information affect people's emotions and whether specific emotions may support comprehension (Level 2 SA) or prompt certain desired behaviors (Level 3 SA). Feedback affective property motivates this research to propose and explore whether the GUI design can support users' comprehension (Level 2 SA) of the infection risks and arouse users' motivation to practice infection prevention more diligently in order to avoid their personal occupational exposure to ABROs (Level 3 SA). Visualization of the MIS mimicking the bacterial inflammation classical symptoms: *Rubor* (redness), and *Tumor* (swelling) may arouse the emotions in HCPs and prompt Level 2 SA (Figure 3.2).



Risk of ABRO Transmission

An important piece of information from the infection prevention perspective is awareness of patients' carriage of ABRO. However, Rothman pointed out that biosurveillance alone may be insufficient for understanding the risks of transmissibility.[73] Rothman urges that the monitoring of disease alone is

insufficient for preventing exposures or altering behaviors causing infections. He recommends monitoring exposure or behaviors that predispose to disease as part of surveillance to guide prevention activities. The spread of infectious disease depends on many factors, including disease-related factors, social factors, demographic factors, geographic factors, and economic factors.

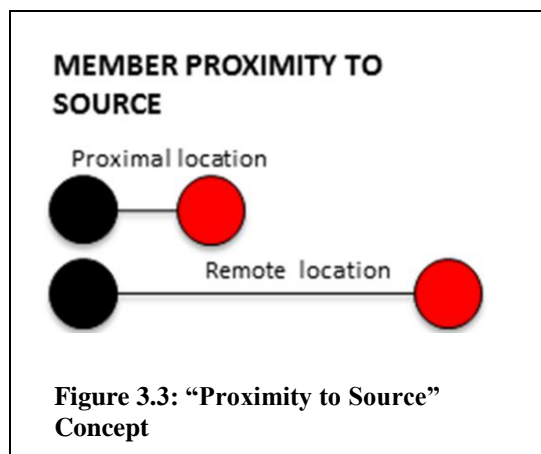
The disease-related factors include infectious agent, mode of transmission, latent period, infectious period, host susceptibility, and ABROs. Social factors are described as frequency and number of contacts while behavioral factors often relate to adherence to rules or guidelines. Geographic factors, such as location and place, are important for estimating a proximity to the source of infection and understanding a distribution of disease. Economic factors include the availability of clean water, sewer systems, and technologies preventing the spread.[73]

Risk of Exposure to an Infectious Agent

There are two types of infectious disease spread: epidemic and endemic. An epidemic is an unusually large, short-term outbreak of the disease. An endemic is a local, persistent disease in a population. Hospitals experience HAI endemic outbreaks [145-147]; however, hospitals can also experience a rapid increase in the number of patients with community-acquired infections. Sattar et al. stated that the demographic structure of the human population increasingly facilitates urban crowding, favoring host-to-host contact and the dissemination of infectious disease among the population.[148]

The microscopic size of infectious agents creates the challenge of quantifying exposure. Proximity to an infectious patient is a commonly accepted surrogate measure for exposure (Figure 3.3). The degree of exposure that leads to infection varies substantially in different patients and depends on many factors. In hospitals, patients may become at risk of exposure to ABRO due to their arrangement on a unit. Those patients who are arranged in a close proximity to each other are more likely to share the same HCPs and be exposed to each other's infections.

Recent research studies emphasized the role of nurses and nursing aids in the spread of ABROs.[22, 23] Knowing the proximity (low spatial resolution data) of a susceptible patient to a patient or patients with ABRO(s) may improve HCPs' SA about risk of transmission and exposure.



Application

The ABRITSA Model should include the concepts “**Exposed**” to describe the individuals who are at risk of exposure to ABR infections due to their proximity to “**Source**”. Anyone can become exposed in hospital regardless of his or her initial MIS. Taking into account that “Source” is represented by two states (CI+ and C-I-) and all MISs include four states (CI+, C+I-, C-I+, and CI-), a total number of the possible exposure scenarios is eight (Picture 3.4). When information about the individual infection state and location represented together, it may be easier for the users to identify subjects at risk of “Exposure”. Therefore, a concept “**Location**” is important. Displaying both patients’ locations and their infection state may facilitate the user’s Level 2 SA about individuals at risk of exposure.

Analysis of disease spatial distribution (incidence and/or prevalence) and patterns are used frequently within epidemiologic studies for mapping transmission hotspots.[149-151] John Snow was the first physician who developed disease mapping for investigating the cholera outbreak in England in 1854.[152] The spatially-linked MIS of each patient may support tactic or strategy development at a delivery group level.

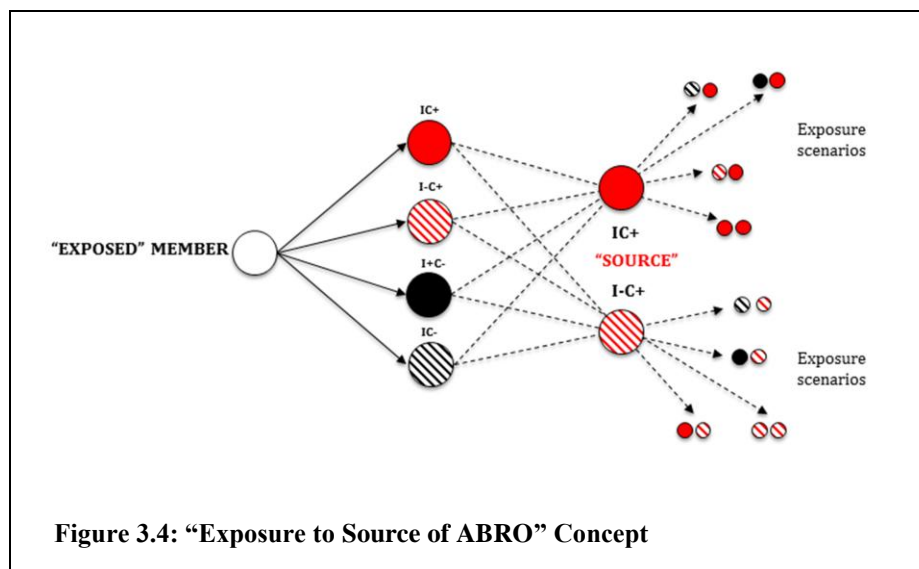


Figure 3.4: "Exposure to Source of ABRO" Concept

Risk of the Progression of Exposure to Infection

The next group of factors concern the development of infection in individuals. These factors involve (1) dose-related factors of exposure, (2) infectious agent, and (3) host-related risk factors.[73] Dose-related factors, such as concentration of the organisms, duration of the exposure to these organisms, and intensity of contact are reliable predictors of the likelihood of infection.[153].

Concentration of ABRO: Rothman explains that exposure to a large number of organisms increases the likelihood of developing infection.[73] Infected individuals have substantial variability in the number of organisms they produce over time. It is challenging to quantify the dose of microorganisms shed. Patients with active ABR infections produce more ABRO than patients who are asymptomatic carrier. The *onset of colonization with ABRO* diagnosed at the time of positive bacterial cultures may potentially serve as a surrogate measure of the bacterial concentration (*bacterial load*) and environmental contamination. The receipt of antibiotics may also signal that a patient is infectious and may shed a considerable amount of microorganisms. The individuals infected with ABROs can introduce the microorganisms to the environment over an extended period. If an asymptomatic patient has a history of colonization with the onset a long time ago, then it is more likely that the concentration of an ABRO is low, and the risk of infection transmission from this patient is minimal.

Contact intensity (frequency of contact) between the susceptible person and the ABRO colonized person also affect the likelihood of infection transmission. Contact intensity between HCPs and patients is especially critical for infection transmission when the patients have active nosocomial infections.[73] The likelihood of transmission of an infectious agent from an infected person to a susceptible person increases when contact duration and contact intensity increase.[18] Reproduction ratio (R_o), an important epidemiologic indicator, measures the frequency of infection transmission and is defined as the average number of secondary cases of an infection that occur in a completely susceptible population following the introduction of a single infectious case.[73]

R_o is high when one case generates many secondary cases. Different infection agents have different values of R_o . When R_o is high, a very short and non-intense contact has the potential to confer infection. When R_o is low, high levels of contact repetitiveness and contact clustering are required for generating secondary cases. Some infectious diseases with comparatively low R_o estimates and low numbers of contacts still qualify for potential transmission. Methicillin resistant *Staphylococcus aureus* (MRSA), for instance, is an infectious agent mostly transmitted in health care and nursing institutions via close physical contact. MRSA's R_o estimates published in the literature show low transmission probability of MRSA.[154] Although MRSA's R_o is low (1.32), health care settings with high levels of contact repetitiveness and clustering facilitate its spread.[18] The transmission interactions in a population are very complex. Therefore, **contact intensity (frequency)** is more convenient in predicting the transmission than R_o .

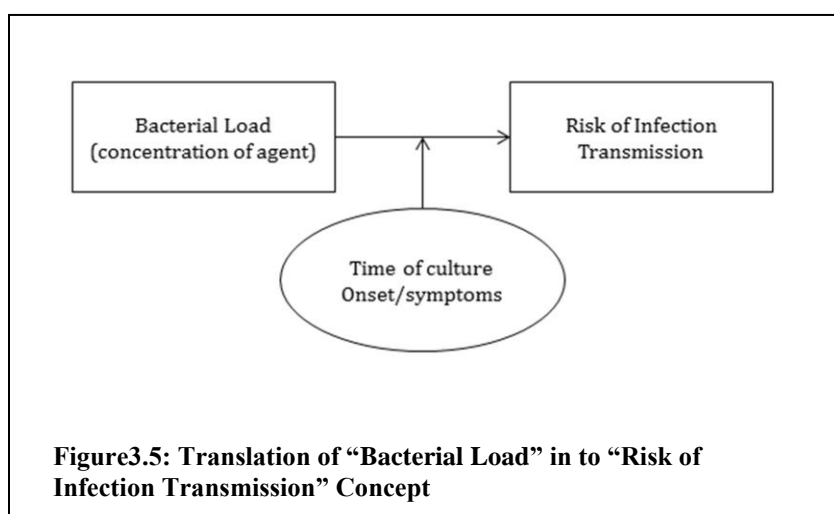
Application

The ABRITSA Model should consider the following concepts, (1) "Intensity of Exposure" (contact frequency) and (2) "Concentration of Agent" (bacterial load).

The concept "Concentration of Agent" can be represented by a surrogate measure, "bacterial load", expressed with a temporal dimension. Taking into account that the highest concentration of an ABRO appears during the infectious period when a patient has symptoms of infection, the temporal information on the clinical cultures can be used for bacterial load. When active surveillance cultures (ASC) are not routinely performed, the clinical cultures are ordered for special reasons, especially when patients

show some symptoms of infections. The most **recent positive cultures** indicate that the patient may be a significant source of infection, although the exact onset of an infection is difficult to identify. A calculation of the difference between the date of the positive culture and any other date, expressed as the number of days, provides the **temporal dimension**.

The bacterial load, an important risk factor of infection transmission, can be renamed to a new concept “**Risk of Transmission**” determined by the time of the positive for ABRO clinical cultures (Figure 3.5). The concept “Risk of Transmission” meets SA-design principles, such as the reduction of the requirement for people to make calculations and the representation of the information timeliness. “Risk of Transmission” can be represented with discrete levels (e.g., < 3 month, 3-6 months, > than 6 months) to streamline the comprehension process (Figure 3.5).

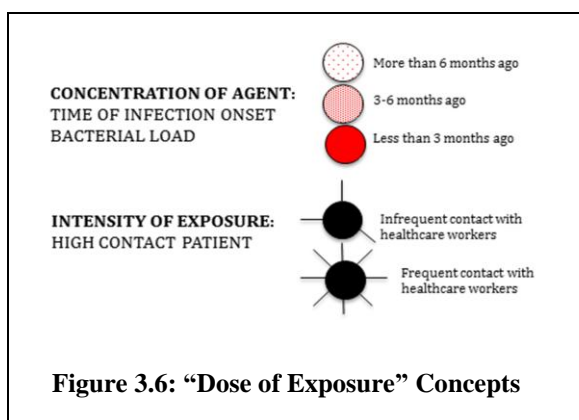


Frequency of contacts can be represented with different data depending on the technology and type of available data. For instance, several studies and practices utilize high radio frequency wearable devices (RFID) to track contacts in the hospital settings.[22, 88, 155] Other studies utilize surveys, chart review, and EHR data. One study reported on types and duration of specific clinical events where nurses and nursing assistants had close contacts with patients.[88] Contact events include catheter care, patient change position and percussion every two hours, bed bath once a day, NG-feeding, body weight checking, change dressing and wound care, injections, blood sugar tests, body temperature measure, suction, line and ventilator circuits change, transferring patient to another ward, assisting with medical procedure and

investigations, and others. The studies on frequency of contacts introduced a term “**super-spreaders**” to characterize HCPs who have the most frequent and prolonged contacts with the patients. The use of EHR data for identification of high contact patients may be feasible for those hospitals that adopted EHRs. For example, Cusumano-Towner et al. (2013) study utilized time-stamped data from EHR for quantifying contacts.[156]

Those patients who require external assistance experience more contacts with HCPs. For example, one study showed that the least dependent patients attract 2.3 minutes per hour of nursing time of face-to-face direct nursing care per hour while the most dependent patients require 5.7 times that and receive approximately 13 minutes per hour of nursing care.[157] It is reasonable to think that dependent patients, those who require maximum assistance, experience more contacts than independent patients do. Therefore, patient dependency status can serve as a surrogate measure of contact frequency.

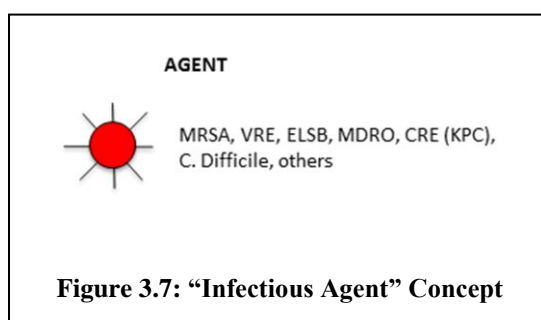
Patient dependency may also serve as a signal that compliance with infection prevention in this patient may be at risk. For example, Chang’s study shows that dependent patients increase workload for shift.[88] Elaborating on the Theory of Goal Setting, one may assume that the presence of a dependent patient would lead to a potential conflict related to user multiple goals and resources, such as time and attention. For example, one study identified that infection prevention guideline, emergency situations, and patients’ discomfort with standard precautions significantly contributed to nursing non-compliance with standard precautions.[158] Contact frequency should be included in the ABRITSA model and labeled “**High Contact Patient**” as a surrogate measure of intensity of exposure (Figure 3.6). “Bacterial Load” (risk of transmission) and “High Contact Patient” may represent critical cues supporting HCP’s Level 2 SA about transmission risk.



Many host-related factors or susceptibility factors influence the occurrence of infection. Persons with altered immune system include elderly, patients who receive immunosuppressive medications or chemotherapy, and patients with inherited or acquired defects of the immune system.[73] Swartz stated that new aggressive medical technologies for diagnosis and therapy (not anti-infective) reduced the incidence of pathologies, such as cancer and diseases of the elderly, at the cost of increasing the problem of infections due to opportunistic or nosocomial microorganisms.[159] Nosocomial organisms, often low-virulent infections, play an increasing role in causing infections in severely ill patients or those people who are densely clustered (e.g., nursing home, hospitals).[141] Information about patient susceptibility to infection and the location of patients with particular infectious agents may be useful for decision-making on patient placement and staff assignment in a hospital setting.

Application

The ABRITSA model should include two concepts named “**Agent**” (Figure 3. 7) and “**Susceptibility**”.



3.4. Summary

Chapter 3 discussed the development of the context and the elicitation of the subsequent risk factors: *infectious agent, member susceptibility, member infection state, location, source location, exposure, intensity of exposure (high contact, duration of exposure), and risk zone (bacterial load)*.

Key Points

- Epidemiological research often uses surrogate measures for determining the exposure to infectious agents (e.g. being in proximity) and quantifying the dose of exposure.
- The accuracy of these measurements may be imperfect due to incomplete data, the use of estimates, and the ethical issues related to infectious diseases.
- The dose-related factors, such as contact frequency and bacterial load (risk of transmission), are reliable predictors of transmission and the potentially useful descriptors of high risk situations.
- The microscopic size of microorganisms makes them “invisible” to the human eye: a “magnifying” visual effect for the concepts such as “Bacterial load”-“Risk for Infection Transmission” may be needed to provide strong signal related to infection transmission risk to HCPs.

Chapter 4 continues model development and consists of two parts. Part 1 integrates quality measurements into the model. Part 2 is an exploratory study of the local EHR empirical data driven by the model’s informational requirements. The investigator addresses the CDC goal “to rapidly detect patterns and trends in specific populations by integrating infection prevention and control with quality improvement and patient safety measures”. Chapter 4 discusses advantages and disadvantages of using surrogate, proxy, and process measures as well as EHR data.

CHAPTER 4: INTEGRATING QUALITY INTO PRODUCT: DEVELOPING QUALITY CONTEXTUAL FEATURES OF THE ANTIBIOTIC RESISTANT INFECTION TRANSMISSION SITUATIONAL AWARENESS MODEL

4.1. Introduction

Chapter 4 continues the ABRITSA conceptual model development. In this Chapter, the investigator addresses the CDC goal to rapidly detect patterns and trends in specific populations by integrating infection prevention and control with quality improvement and patient safety measures.

Chapter 4 consists of two parts. Part 1 is the knowledge elicitation study aiming at the integration of quality improvement and patient safety measurements into the ABRITSA conceptual model. The investigator provides a literature review on types of quality measurements in healthcare and adopts Deming's quality approach aiming at building quality into product. This part finalizes the ABRITSA model development.

Part 2 represents an exploratory study of the unit dynamic epidemiological environment directed by the ABRITSA model's informational requirements and the local EHR system as a potential source of data. In part two, the investigator describes the sources of data in the local EHR that address the model's informational needs and provides empirical evidence of the daily changes in the unit epidemiological environment with the use of that data.

At the end, Chapter 4 discusses advantages and disadvantages of using surrogate, proxy, and process measures; advantages and disadvantages of using EHR data.

4.2. Part 1: Quality Management Knowledge

The first quality management pioneers developed several principles that are still beneficial today. Improving processes in order to improve outcomes was a primary focus of their early efforts. W. Edward Deming, an industrial quality expert, recommended building quality into the product or services to eliminate the need for mass inspection.[160] He proposed a statistically controlled management process to

determine a range of random variation in the process and causes of variation. All causes of variation can be categorized as common causes vs. special causes. According to Deming's "85/15 theory", 85% of the problems are process-related while 15% are individuals-related. In the 1970s and 1980s, Philip B. Crosby produced evidence that high quality is less costly than waste or workarounds, the typical signs of poor quality processes. He established several methods for quality improvement including setting goals for individuals and groups, meeting and recognizing goals, and removing errors from management. His philosophy for quality was based on the principle "Do it right the first time". Kaoru Ishikawa, the Japanese inventor of the cause-and-effect diagram known as Fishbone diagram, brought up total quality management philosophy. He has advanced quality improvement movement by introducing a method called total quality control, recognizing the entire organizational commitment to quality. Healthcare systems adopted the Walter Shewhart (1920) continuous quality approach, the Plan-Do-Check-Act (PDCA) cycle. Although PDCA has been the most prevalent method of quality improvement in healthcare, the literature does not provide information on resources associated with this approach, sustainability of changes over time, and effects on outcomes. With the growing availability of electronic data, the Deming's approach to quality management, such as building quality into the product or services, appears the most efficient.

Quality Management in Healthcare

A pioneer of quality management in healthcare, Florence Nightingale (1960) hypothesized that processes of care in different hospitals may be different as patient outcomes varied across different hospitals. Boston surgeon, Ernest Codman, described considerable variability in patient outcomes. He strongly encouraged a systematic evaluation of healthcare processes. Later, the American College of Surgeons foundation adopted his principle "track every patient who was treated long enough to determine the effectiveness of the treatment and a need for changes". In the 1950s and 1960s, Avedis Donabedian, M.D., developed a theoretical framework for healthcare evaluation known as "structure, process, outcomes" model. According to this model, patient outcomes can be affected by healthcare structure, including facilities, hospital equipment, provider qualifications, and processes, including activities associated with diagnosis, treatment, and prevention. In the 21st century, a major focus in healthcare quality improvement was placed on patient safety, which in many cases related to medication errors.

Adoption of health information technologies and generation of vast amounts of health data further advance quality management in healthcare.

Quality Measurements

Tenner and De Toro explained that the absence of measurements limits an organization's ability to evaluate the effects of changes and precludes systematic improvements.[161] Performance measurements were defined as a regular assessment of the results produced by the program. According to Tenner and De Toro, performance measurements involve (1) identifying processes, systems and outcomes that are integral to the performance of the service delivery system, (2) selecting indicators of these processes, systems and outcomes, and (3) analyzing information related to these indicators on a regular basis. The purpose of measurement and assessment are (1) to assess the stability of processes or outcomes to determine whether there is an undesirable degree of variation or a failure to perform at an expected level, (2) to identify problems and opportunities to improve the performance of processes, (3) to assess the outcomes as a result of the care provided, and (4) to assess whether a new or improved process meets performance expectations.

Healthcare systems serve innumerable tasks related to both healthcare processes and business processes, such as patient admission, transfer, discharge, diagnostics, treatment, transportation, and safety that need a systematic assessment. Healthcare quality measurements can provide information about processes, services, and patient outcomes.[35] Eddy described three main purposes of performance measurement in healthcare: (1) to describe the effect of an intervention on a specified group of patients (e.g., outcomes studies), (2) to measure an improvement in outcomes caused by a modification of a treatment (a quality improvement program), and (3) to compare the quality of care being delivered by different entities.[162] Many clinical quality measurements were developed to reinforce the evidence-based practice: some measures assess the occurrence of targeted health events and report a rate of their occurrence while other measurements are focused on accountability, inequalities, and productivity of healthcare services. All healthcare quality measurements can be categorized as structure measures, process measures, and outcome measures. It is important to recognize that the effects of using structure vs. process vs. outcome measurements on healthcare quality improvement vary and require cautious interpretations.

Process measures, the most frequently used measurements in healthcare, often lack evidence of their direct effects on clinically desirable outcomes. One observational, nested case-control study identified no difference in the incidence of surgical site infections observed after the implementation of the evidence-based processes, including timing, choice, and duration of antimicrobial prophylaxis.[163] Patient or healthcare practitioner compliance with evidence-best practice is a type of process measures aiming at behavioral issues. Compliance measurements raise another concern; it is believed that they may preclude innovative decision making. This concern calls for a mechanism that would allow refining and adapting process measures over time.[164] In spite of these drawbacks, processes measurements provide several advantages: they can measure processes in real time, target for action, and can be used in different institutions.[165] Kelly and Hurst state that process measures represent the closest approximation of actual healthcare offered and are the most clinically specific.[166]

Process measurements are useful for improving efficiency of healthcare. For example, monitoring and assessing clinical processes are helpful in eliminating waste or inefficiencies. One quasi-experimental study showed elimination of workarounds by monitoring compliance with the improved MRSA infection prevention processes, such as utilization of “visual environment” including floor plans, directing lines on the floors of dedicated isolation rooms, visual management boards for directing patient placement, cohorting rules, and signs for patient isolation.[167] The study also showed that the improved processes resulted in a significant decrease in the MRSA infection rates. Because process measurements can represent the closest approximation of actual healthcare, they can be used for real-time feedback in the SA-oriented design.

Health outcome measurements seek to represent measures of health improvement or deterioration attributable to medical care. Eddy [162] communicated several problems with using outcome measures, including probability, low frequency, long delays, and comprehensibility of outcomes. The main challenge to outcome measurements is that they are highly probabilistic, which means that the expected outcome does not necessarily occur even if the care provided was deemed appropriate. Patient outcomes may be influenced by factors other than quality of care, for example disease severity or age. Therefore, patient outcomes should be risk-adjusted to allow fair comparison across different organizations.[168] Eddy

emphasized that the probabilistic nature of health outcomes makes these quality measurements fundamentally different from quality measurement in most other industries.

Structure measures include organizational characteristics, such as hospital size, volume of procedures, provider credentialing, and technologies. Unlike process and outcome measures, structure measures were found insufficient for improving patient outcomes.[166] Taking into account different aspects of structure, process, and outcome measures, it is believed that process measures are preferable because they are frequent, immediate, controllable, and rarely confounded by other factors.[162]

Health systems also adopt outcomes and processes quality metrics that do not have robust supporting evidence or clear links to substantial improvements in quality or patient outcomes but add value for decision-making on quality improvement.[99] The rationale for these measurements includes an opportunity cost, validation of new mathematical models of disease [162], enhancement of population health, mitigation of health disparities, and population health management [169]. These measurements also enable a learning healthcare system and a data-driven quality management approach.

Infection Prevention and Control Intervention Measures

Several investigators described the infection prevention and control processes as prominently time-consuming activities.[123-125] Infection prevention practices often include (1) hand hygiene; (2) barrier precautions (gloves and gowns) in the care of colonized and infected patients; (3) the use of dedicated instruments and proper technique for inserting medical device(s); (4) isolation precautions; (5) environmental cleaning; (6) instrument sterilization; and (7) the placement of colonized or infected patients in single rooms or multi-bed rooms or areas reserved for such patients. These interventions require coordination and compliance with the process specifications.

Majority of infection prevention and control process measurements assess compliance with broad-based HAI prevention practices that must be practiced consistently by a large number of health care personnel, including hand hygiene and barrier precautions. Overall, process measurements can be categorized into two main groups: an administration of a procedure (compliance measures) and a conformance with the specifications of the procedure (quality assurance measures).

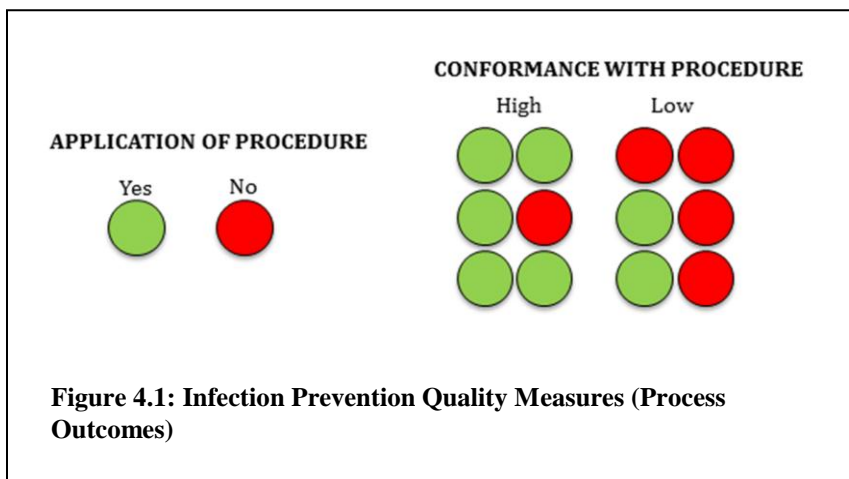
The use of value-added quality measurements for reducing HAIs through health IT has been demonstrated to increase productivity; improve outbreak investigation capability and healthcare practitioners practices; raise awareness about prevention of HAIs in high-risk populations; increase accountability among HCPs; and decrease costs.[170]

Application

The investigator proposes to include a quality measurement concept into the model. Integrating the infection prevention process measurements with the epidemiologic context may increase the understanding (Level 2 SA) about a distribution of the preventive procedure in different groups of patients.

A pilot process measure is “application of procedure”, which is a compliance measure (Figure 4.1). Individuals may experience some side effects caused by the interventions; therefore, it is important to be aware of the individuals who have contraindications for specific procedures or interventions due to intolerance, allergy, and other side effects. An additional concept to be included in the model is contraindication(s) to infection prevention intervention.

There may be situations when the number of infected/colonized patients increases. The information about the compliance or conformance with the infection prevention intervention(s) at this moment may inform the healthcare team about the potential risk for infection transmission and those individuals who are at high risk of exposure.



Intensive care units (ICUs), dialysis, oncology wards, and transplant units are known as high risk for infection and antibacterial resistance units due to high prevalence of multi-drug resistant microorganism colonization and infection. These settings correspondingly have greater demand for contact and enhanced contact precaution regimes, patient hygiene, hand hygiene, and other control measures due to high risk for spread of infection. In order to maximize the benefits of the infection control, it is important to understand both the infectious disease burden (population-based outcomes) and the patterns of actions associated with this burden. Therefore, another useful measure is disease prevalence or disease burden.

Purpose and Attributes of Biosurveillance and Disease Burden

Measuring prevalence of a specific health status or outcome is often used for planning of health resources and facilities. Disease prevalence (burden) can be a useful measure for planning resources at the hospital unit level to ensure adequate staffing for patient safety. According to Rothman, diseases with very low incidence rates may have substantial prevalence if they are nonfatal but incurable. Prevalence is used to measure the occurrence of diseases with no definite moment of onset and infections with a long asymptomatic phase. The surveillance systems help monitor the incidence or prevalence of specific health problem (population-based outcomes) and characterize affected people and those at greatest risk. Trends detected through surveillance data are used to inform and evaluate public health programs and to anticipate future trends, assisting health planners.[73] Monitoring the trends in disease occurrence is the cornerstone objective of most surveillance systems. The detection of an increase in adverse health events can alert hospital or health agencies.

Surveillance has the following attributes: sensitivity, timeliness, predictive value, representativeness, data quality, simplicity, and flexibility.[73] *Sensitivity* of surveillance relates to the accuracy of identifying all targeted events. *Low sensitivity* may be acceptable for the purpose of monitoring trends if sensitivity is consistent over time and detected events are representative. However, for assessing the impact of a health problem, high sensitivity is required. *Timeliness* of surveillance, a temporal attribute of the infection data, depends on the urgency of a public health problem. *Simplicity* of surveillance relates to the quantities of and meaningfulness of data. A trade-off between the amounts of data vs. its

meaningfulness needs to be recognized. *Flexibility* of surveillance relates to the system capability to adapt to new circumstances or changing information needs.

Utilizing Biosurveillance Data for Measurements of Infection Burden in Hospitals

Observed trends in disease incidence combined with other information about the population at risk can be used to anticipate the effect of a disease or the need for care.[73] Surveillance may provide an inexpensive and sufficient assessment of the effect of intervention efforts.

The Society for Healthcare Epidemiology of America and the Healthcare Infection Control Practice Advisory Committee developed several metrics to measure infection exposure burden in hospital settings.[8] The infection exposure is defined as the amount of exposure that patients in a healthcare facility have to patients who are either colonized or infected with ABROs, and who could potentially transmit the MDRO to them. The infection exposure burden is often called colonization pressure, which is an independent risk factor for healthcare acquisition of MRSA, CRE, VRE, MDRO, Extended-spectrum β -lactamase-producing Enterobacteriaceae (ESBL), Clostridium difficile (C. difficile), and others. Colonization pressure significantly correlates with the risk of transmission in hospitals.[171-173] Cohen et al. recommends a simple approach to help healthcare facilities make a judgment on whether exposure levels are high, and to explain if there is any ongoing transmission of ABROs. [8] Exposure burden can be measured with *overall ABRO prevalence* and *admission ABRO prevalence*.

When active surveillance cultures (ASC) are not routinely performed, the overall ABRO prevalence is based on clinical cultures from the specimens from identified patients with ABRO isolates and the specimens from patients with a history of colonization. Cohen et al. emphasized that this method significantly underestimates the full reservoir of infection, and puts in the picture only the tip of the “resistance iceberg”. If active surveillance cultures are not performed, this measurement may underestimate the true infection burden.

Another measure of infection exposure burden is the ABR admission prevalence. This metric identifies the magnitude of importation of an ABRO into the facility. It helps identify whether importation is due to the readmission of recently discharged patients or the transfer of patients from other healthcare facilities. The numerator includes patients with ABR isolates identified and patients with a history of

colonization. The prevalence rate of ABR infection or colonization is the total number of patients with ABRO in a specific population during a specific period per 100 patients admitted to the hospital.[174] Several studies provide evidence that colonization pressure depends on crowdedness and the colonization density, measured as a number of colonized patients in a particular area.[171-173] Colonization density may be useful for comparing the infection burden in different settings.

Pelupessy et al. reported that hospitals that reduce the incidence of resistance may see no reduction in overall prevalence due to a steady increase in the number of asymptomatic carriers entering hospitals.[175] The investigators stated that patients diagnosed with an infectious disease caused by ABRO remain hospitalized until the symptoms are cured, but they may continue to carry and shed them for months or even years. The study showed a prevalence of ABROs in hospitals rapidly approached equilibrium because of the rapid turnover of patients with the average length of stay of five days.[175] Hospitals tend to establish practices associated with a short length of stay and high bed utilization rates. Such practices, however, enable a constant influx of new patients, many of whom may be asymptomatic carriers.

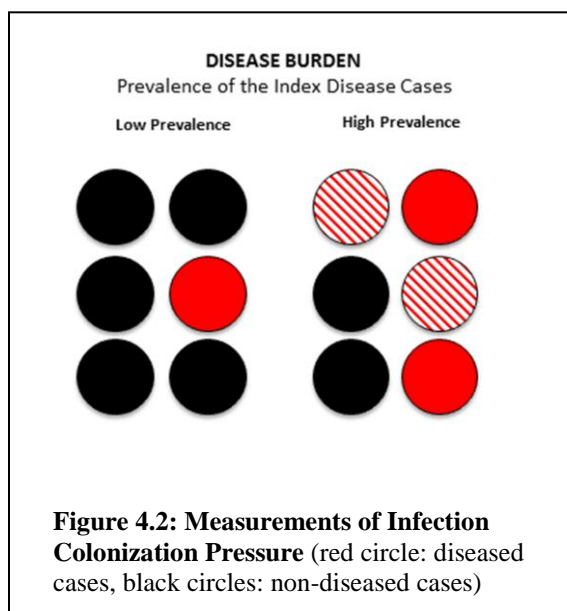
On the flipside, Smith et al. study [130] found that the slower turnover of patients in long-term care facilities may yield a much higher single-stay reproductive number (R_0), which implies that extended stay in long-term care facilities may play a very important role in spreading antibacterial resistance. Per Smith et al. (2004), the increase in the proportion of carriers in hospitals admitted from long-term care facilities, other hospitals, and the community contribute to the growing prevalence of ABR resistance in hospitals.[130] Also Smith et al. showed that the prevalence changed rapidly in response to changes in hospital infection control.

Measurement of infection prevalence (colonization pressure) in a specified enclosed location is feasible for use in practice; it informs about the infection burden in this particular setting. Colonization pressure significantly correlates with the risk of transmission.[130]

Application

Prevalence of patients colonized with ABRO (infection burden) may be a useful indicator for the situational awareness design. The ABRITSA Model should include the concept “Infection Burden”. A

measurement of unit colonization pressure (UCP) is defined as the number of colonized patients per 100 patients in a unit for a specified period of time (e.g., a 24-hour period).



Information on a unit daily prevalence of colonized patients may improve the healthcare team's understanding, Level 2 SA, of infection burden and facilitate Level 3 SA (e.g., decision making for timely adjustment in resource allocation, planning, and infection prevention and control strategies and tactics).

Table 4.1 summarized all the concepts identified for the ABRITSA model in Chapter 3 and Chapter 4. All these elements represent the critical cues for identifying the implicit cognitive concepts, such as infection transmission areas (*transmission hotspots*), subjects at high risk of exposure, super-spreaders, and super-hosts. In this study, transmission hotspot is defined (1) as a spatial cluster of the carriers of antibiotic-resistant organisms (e.g., adjacent wards occupied by the carriers of ABROs) and (2) as a location visited by the super-spreaders (e.g., a coffee break room visited by a super-spreader). Super-spreaders are defined as individuals who experience frequent contacts with colonized and/or infected individuals. Super-hosts are defined as individuals with alerted immune system.

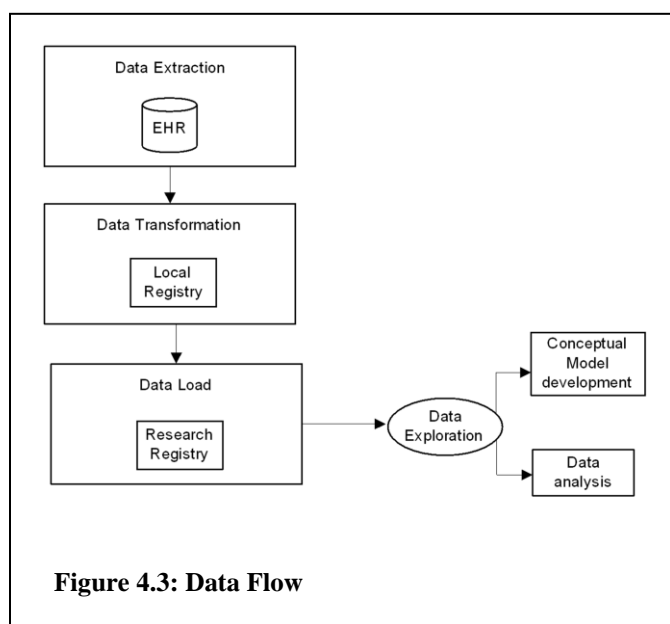
Table 4.1: The Infection Prevention Situational Awareness (ABRITSA) Model Contextual Features

CONCEPT	CONTEXTUAL FEATURES
AGENT	
INFECTIOUS AGENT	MRSA, VRE, C. Difficile, ELSB, MDRO, Ext Pseudomonas, Others
MEMBERS	
MEMBER SUSCEPTIBILITY STATE (out of scope)	High Susceptibility (e.g., patients with cancer, transplant, immunodeficiency, on dialysis, or elderly) Low Susceptibility
MEMBER INFECTION STATE (MIS)	<u>Infection States</u> : IC+, I-C+, I+C-, IC-. <u>Source</u> : IC+, I-C+.
LOCATION	
LOCATION (WARD NUMBER, BED NUMBER)	Location of the rooms in the setting(s)
COMMON CIRCUIT	A common area where the adjacent rooms' doors open in
ACTION	
APPLICATION: RECEIPT OF THE INFECTION PREVENTION INTERVENTION	Receipt of an infection prevention intervention
CONFORMANCE: UNIT INFECTION PREVENTION PERFORMANCE	Unit compliance with the infection prevention guidelines measurements
CONTRAINDICATION(S) TO INFECTION PREVENTION INTERVENTION	Allergy, Intolerance, Health conditions, etc.
DISEASE BURDEN	
UNIT INFECTION BURDEN	Colonization pressure: prevalence of patients with a history of colonization or infection caused by antibiotic resistant organisms on a unit on a given day Antibiotics use: prevalence of patients who receive antibiotics on a unit on a given day
LIKELIHOOD OF TRANSMISSION	
SOURCE LOCATION (SPATIAL DISTRIBUTION)	Location of the colonized patients: HAZARD ZONE
EXPOSURE: PROXIMITY TO SOURCE	Member location proximal to "HAZARD ZONE"
HIGH CONTACT PATIENT (HCP) (INTENSITY OF EXPOSURE)	Patients who require maximum assistance and experience frequent contacts with HCPs
DURATION OF EXPOSURE	Number of days patients spent in a close proximity to colonized patients
HAZARD ZONE: RISK OF TRANSMISSION	BACTERIAL LOAD (ABRO concentration) <u>Significant Risk</u> : the onset of ABR infection is less than three months ago <u>High Risk</u> : the onset of ABR infection is more than three months ago
POTENTIALLY CONTAMINATED COMMON CIRCUIT	Circuits where at least one adjacent room is occupied with a colonized patient (s)
UNIT DENSITY OF INFECTION	Density of the colonized patients in a specific location

4.3. Part 2: Exploration of Variations in the Unit Epidemiology

The objective of this part was to explore the study EHR biosurveillance and other sources of data. Specifically, the study looked at (1) a variance in the number of patients with different “infection states” (MIS), (2) a variance of “high contact” patients with status “IC+”, “I-C+” and “I+C-“, and (3) a distribution of patients who did not receive chlorhexidine bathing (no “receipt of infection intervention”) among “IC+”, “I-C+” and “I+C-”.

Data Acquisition: A query was developed in the EHR. The report automatically uploaded at midnight and abstracted all needed data from the documentation produced during the previous 24-hour period (temporal resolution). The system sends the report as an Excel spreadsheet (XLS) file every morning (Figure 4.3).



Data Sources, Elements, and Definitions:

The electronic report abstracted the infection surveillance data, antibiotic use data, patient assistance status, patient’s receipt of chlorhexidine bathing, and allergy data (Table 4.2). The sources of data included: (1) admission/discharge/transfer module (ADT), (2) medication administration module (MAR), (3) allergy note (AN), (4) infection control note (ICN), and (5) nursing hygiene note (NHN).

Study operational definitions for the main ABRITSA concepts:

The provided definitions are tailored to the local practice and EHR data.

(1) Patients are classified “**C+**” (**colonized**) if they have at least one ABRO documented in the EHR infection preventionist note. The inclusion criteria for ABROs are Methicillin resistant *Staphylococcus*, *C Difficile*, Extended Spectrum Beta Lactam resistant, Extended Resistant *Pseudomonas*, Vancomycin Resistant *Enterococcus*, Linezolid Resistant Vancomycin Resistant *Enterococcus*, Carbapenemase Producing Bacteria, Multi-Drug Resistant *Pseudomonas*, Multi-Drug Resistant Gram Negative Rod, and Extended Resistant *Pseudomonas*) (Table 4.2).

(2) Patients are classified “**I+**” (**infected**), regardless of the etiology of infection, if they have their EHR data indicating the administration of intra-venous (IV) and/or oral (PO) antibiotics. Bactrim and oral penicillin are excluded as a prophylaxis.

(3) The concept “**unit colonization pressure**” (UCP) is defined as a proportion of unit patient population with a history of ABRO(s) or clinical cultures positive for ABRO(s). The denominator for UCP is based on mid-night unit census for a 24-hour period.

(4) The concept “**intensity of exposure**” is converted into a proxy measure, such as “high contact” patients. “High contact” patient implies that patient experiences frequent contacts with HCPs. This status is determined from the EHR nursing hygiene note indicating a need for “maximum assistance”.

(5) For this study, the investigator chose one infection prevention intervention for the concept “**application of infection prevention procedure**”: patient chlorhexidine bathing.[176-179] The source of this data is an EHR time-stamped nursing note on hygiene. The hygiene template listed the following outcomes to choose-*full bath, partial bath, showered, peri-wash, pre-procedure scrub, Chlorhexidine used, and patient refused*. The numerator for the process measurement is a receipt of chlorhexidine bath by a patient. A receipt of the chlorhexidine bath is documented in the EHR nursing hygiene note.

(6) The concept “**hazard zone: risk for infection transmission**” is defined as a location or ward occupied by “C+” patients. The hazard zone has one modifier “Significant risk”, which is determined by a difference between the time of clinical culture data and a given day. When the difference is less than 3

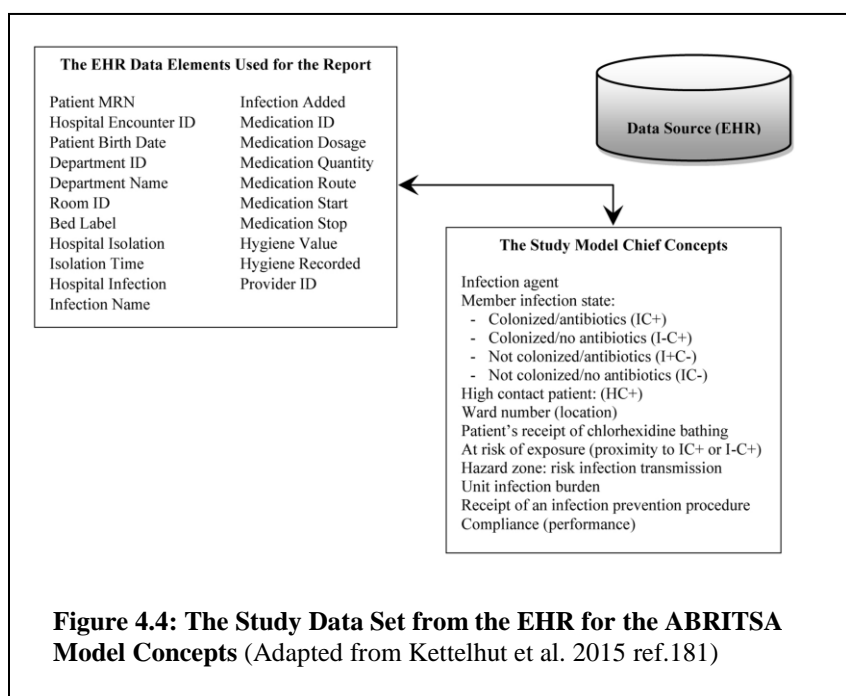
months then the risk of infection transmission is rated “significant”. The study EHR provides the time-stamped infection surveillance data in the ICA.

(7) Patient **susceptibility** to infection depends on patient’s immune system function. This concept is very important, however, it will be explored in further studies.

(8) Duration of exposure, a longitudinal measure of patient days being in proximity to or contact with “Source”. This concept will be explored in further studies.

(9) The concept “**contraindications** for infection prevention intervention” is defined as a health condition precluding patients from receiving chlorhexidine bathing. The information about allergy or intolerance to the chlorhexidine products (CHG) is documented in EHR allergy note.

Figure 4.4 provides the data elements abstracted by the electronic report.[180]



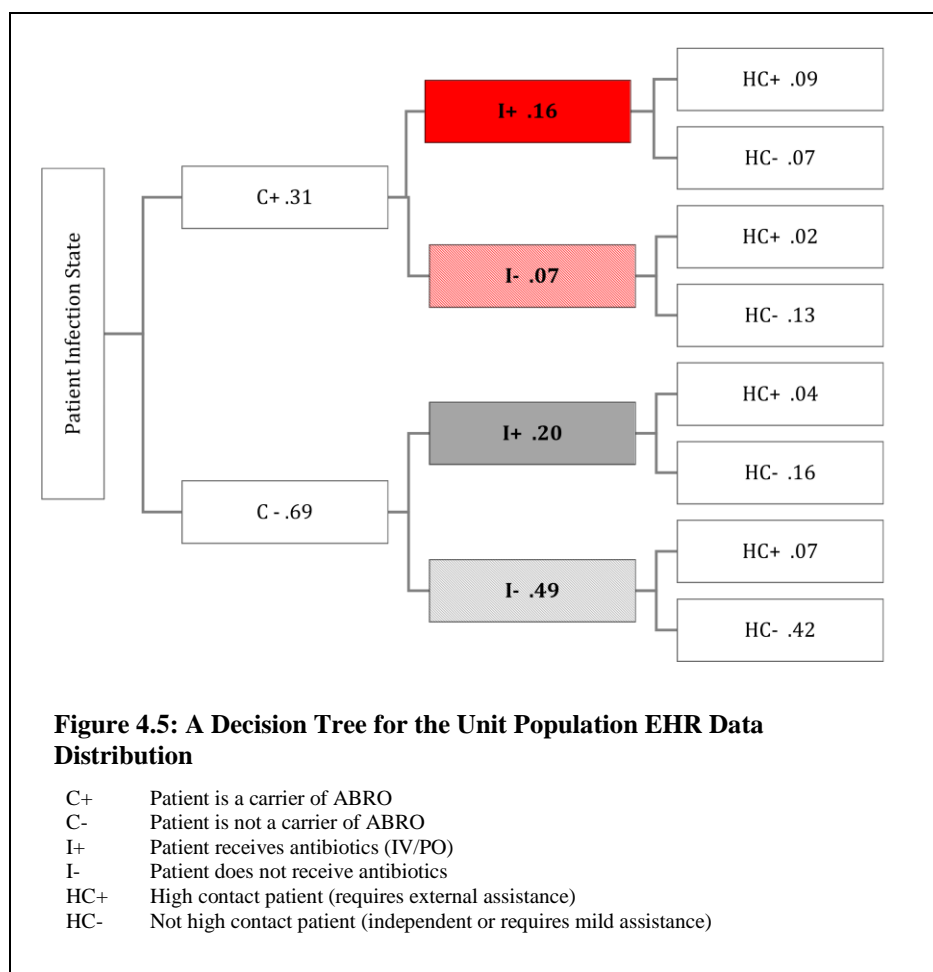
Data Normalization and analysis: Patient data were de-identified. The EHR was collected for a seven-day period in 2014. The data were normalized and computed. The following measurements were produced: unit daily census, unit daily prevalence of colonized patients (“C+”), unit daily prevalence of patients who received antibiotics (“I+”), unit daily prevalence of patients who require maximum assistance

(“HC+”), and unit daily prevalence of patients who received chlorhexidine bathing (“CHG+”) stratified by MIS. The denominators were based on the unit daily midnight census, and the numerators were based on the specific criteria (Table 4.2).

Table 4.2: Sources of Data, Data Elements, and Measurements

Data Sources	Measurements	Numerator	Data Elements Used
<i>Admission/Discharge/Transfer (ADT)</i>	Daily unit census	Patients on the unit on a given day- (denominator)	Patient MRN Hospital Encounter ID Department ID Department Name Room ID Bed Label
<i>Medication Administration Record (MAR)</i>	Prevalence of patients who received antibiotics	Patients who received antibiotics on a given day	Medication ID Medication Dosage Medication Quantity Medication Route Medication Start Medication Stop
<i>Allergy Note</i>		Patients who have allergy to chlorhexidine product (CHG)documented in the EHR allergy note	Chlorhexidine Gluconate Chlorhexidine Gluconate/Brush Chlorhexidine HCL
<i>Infection Control Note</i>	Daily colonization pressure (disease burden)- census	Patients who have at least one ABRO: <ul style="list-style-type: none"> • Methicillin resistant Staphylococcus • C. Difficile • Extended Spectrum Beta Lactam resistant • Extended Resistant Pseudomonas • Vancomycin Resistant Enterococcus • Linezolid Resistant-Vancomycin Resistant Enterococcus • Carbapenemase Producing Bacteria • Multi-Drug Resistant Pseudomonas • Multi-Drug Resistant Gram Negative Rod • Extended Resistant Pseudomonas 	Hospital Isolation Isolation Time Hospital Infection Infection Name Infection Added
<i>Nursing Hygiene Note</i>	Daily census of patients who received chlorhexidine bathing (CHG) Daily census of high contact patients “HC+”	Patients who had chlorhexidine full bath, partial bath, or shower on a given day Patients who required maximum assistance for hygiene	Hygiene Value Hygiene Recorded Provider ID

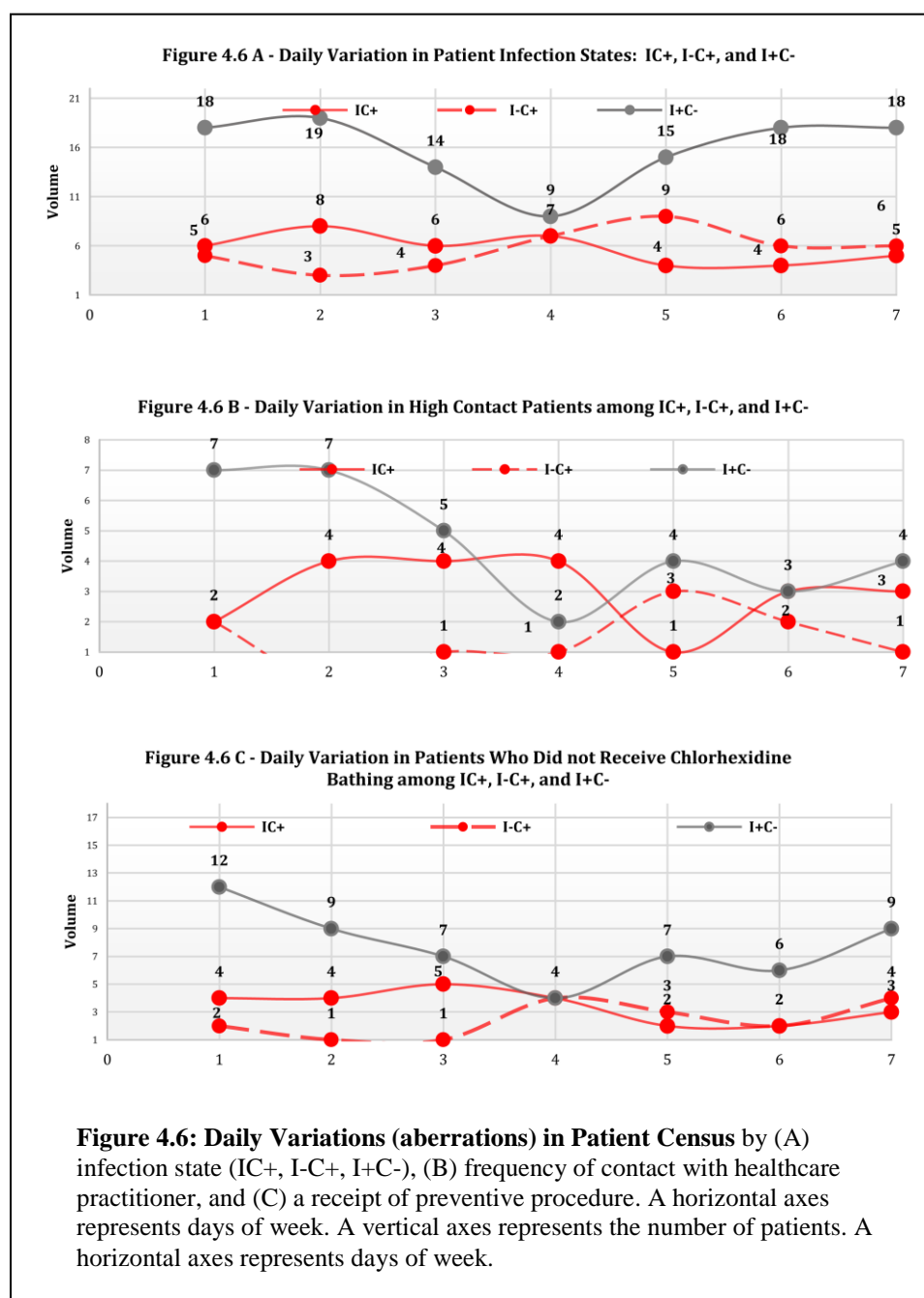
Results: The data were graphically and quantitatively examined. During the reported period, the daily census of patients ranged from 45 to 47 patients. A decision tree was constructed to understand the empirical distribution of the mean prevalence of patients by their infection state (Figure 5.7).



During a seven-day period, on average, 69% of the unit population were non-carriers of ABROs (“C-”) while 30% of the patients were carriers of ABRO (“C+”). Thirty-six percent of the unit population, on average, were documented as recipients of IV antibiotics “I+”, of whom 20% were “C-” and 16% were “C+”. The mean proportion of the high contact patients (HC+) was 22%, consisting of 11% of the carriers of ABRO (“C+”).

In addition, the three diagrams were produced to investigate daily variations in the distribution of the infection transmission characteristics for the reported period among the patients who were categorized as IC+, I-C+, and I+C (Figure 4.6 A, B, C). The diagrams showed daily fluctuations (increase and decrease) in the prevalence of IC+, I-C+, and I+C- categories of patients (Figure 4.6 A), the intensity of

contact (high contact) (Figure 4.6 B), and the receipt of the infection prevention intervention (Figure 4.6 C). This information provides pilot evidence on the unit daily changes in disease burden and risk factors.



The EHR data showed that allergy and intolerance to chlorhexidine were rare in the study population.

4.4. Discussion

The literature lacks evidence on whether flagging patients with known ABRO colonization and infections in the EHR and monthly reports on HAI rates are sufficient for reduction of the spread of ABR infections. In this study, the investigator has developed the ABRITSA conceptual model and examined the contextualized infection prevention data set comprising of the critical cues pertinent to the risk of infection transmission. The model aims to support sense making in team's SA about at-high risk for infection transmission locations and subjects at high risk of exposure to ABROs in near-real time.

Inclusion of Surrogate, Proxy, and Process Measures to the ABRITSA Model

The ABRITSA model has integrated the quality measurements with the epidemiological context. The model concepts represent (1) the surrogate measures of infection transmission, such as proximity to source of infection, intensity of exposure, and significance of infection transmission risk, (2) a proxy measure, such as disease burden (prevalence), and (3) the quality measures estimating daily compliance with infection prevention intervention. A combination of the feedbacks on local environmental changes related to disease burden, domain specific risk factors (epidemiological context), and on the gaps in observed performance (quality measurements) may (1) reduce environmental uncertainty, (2) identify opportunities in operational setting for targeted tactics, and (3) improve reliability of practice.

Advantages and Disadvantages of Using Surrogate and Proxy Measures

The proposed surrogate, proxy, and process measures in the ABRITSA model provide qualitative data about daily variations in high-risk for infection transmission subgroups of patients. Weinstein and Huang (2009) describe a critical need to measure HAI and infection transmission by using proxy measures in addition to universally available exact measures.[32] They believe that surrogate or proxy measures of the infection transmission risk are important contributors to a rapid assessment of ABROs and infection prevention practice. Easy capture and opportunity to measure processes and outcomes in real time are the main reasons why surrogate and proxy measures can be widely accepted. For example, the infection prevalence measures can be used for assessing the potential for ABRO transmission risk in real time. The reduction in disease burden may be as important as the reduction in the hospital-acquired episodes. The infection prevention process measures, such as compliance measures, presented in the context of infection

burden may provide a considerable value for priority management by informing the users about the underuse of infection prevention in the patient subgroups.

Proxy, surrogate, and exact measures have advantages and disadvantages leading to some limitations in using them. For example, proxy measures' numerators or case count can be affected by different clinical practices. Some practices perform active surveillance cultures and screen all patients admitted to hospital on a carriage of ABRO(s) while other practices use only clinical cultures leading to underestimations of the true ABRO prevalence.[8, 10] Also, HAI proxy and surrogate measurements are approximations of the risks. In contrast, HAI exact measures provide certainty because they are based on the rigorous definitions and criteria developed for evaluation of the effectiveness of infection prevention and control programs. On the other hand, unlike proxy measures, exact measures are retrospective, time consuming, and not suitable for supporting situational awareness and decision making in real time.[32] Thus, it is important to have proxy and surrogate measures with relatively good predictive value. The predictive value is determined by a degree to which proxy or surrogate measures correspond to exact measures. The ABRITSA model's proxy, surrogate, and process measures have evidence of their high predictive value for infection transmission and acquisition of HAIs.

The inclusion of the process measure, such as compliance with infection prevention and control, in the ABRITSA model was motivated by the fact that process measures, when comparing with structure and outcome measures, are preferable because they are frequent, immediate, controllable, and rarely confounded by other factors.[162] The ABRITSA compliance (process) measure, such as a receipt of chlorhexidine bathing, can be used for a feedback on individual HCP's performance. Providing individual feedback has the highest effect on individual performance.[59] This feedback may reinforce infection prevention practice. This information would help target quality improvement efforts and subsequent improvement.

Consequently, the compliance data in the light of epidemiological local context may be important for supporting Level 2 SA (comprehension) and Level 3 SA (projection) leading to better decision making on situational tactics.

Measurement Definitions and Sources of Data

The investigator developed the definitions for the model's concepts and identified the sources of data in the local EHR. It is important to recognize that the proposed definitions and sources of data are subject to change. Some model's concepts may require refinement in the context of their value for improving situational awareness and decision-making in different healthcare practitioners. For example, the MIS concept "I+" (infected patient) requires further understanding about its informational value in communicating the ABRO transmission risks. Identifying patients who receive antibiotics may be important for supporting Level 2 SA and Level 3 SA. The use of antibiotics is a considerable contributing factor to antibiotic resistance.[145, 181, 182] Overutilization and misuse of antibiotics has become an international issue that needs immediate attention and actions. The data on antibiotics administration are readily available in EHRs and easy to capture unlike accurate diagnoses of infections. Representing antibiotic data within the local epidemiological context may address situational awareness needs of a different stakeholders group (e.g. antibiotics stewardship).

The rationale for the concept "Significant risk" of transmission or "bacterial load" is to describe a high-risk for infection transmission areas, so-called hotspots for transmission. The investigator has decided to use a temporal dimension of the clinical cultures (e.g., < 3 months vs. > 3 months) to represent the concentration of an ABRO in individual patient. However, there may be other solutions as to how to determine "bacterial load". In addition, there may be other choices for describing high-risk for infection transmission zones. For example, this concept may be determined by type of ABRO(s). It is documented that some ABROs are associated with high morbidity and mortality (e.g., Carbapenem-resistant infections) while other ABROs are associated with high environmental survivability (e.g., *C. Difficile*) or ability to share its genetic material containing drug-resistance with other bacteria (e.g., *Enterococci*). The knowledge about health effects and impact on infection prevention methods associated with each type of ABRO may provide additional value for improving SA in different healthcare team members.

The investigator provided the pilot definitions for the concept for exposure, a risk factor predisposing individuals to infection transmission. For example, the intensity of exposure measure ("high contact" patients) and the compliance measure with infection prevention ("receipt of chlorhexidine bathing") can have different sources of data or methods of measurements. The ABRITSA model concept

“high contact” patients, representing frequency of contacts between patients and HCPs, is a strong predictor of infection transmission.[22, 23] Although the investigator proposed to use patient’s dependency status as a surrogate measure for this concept, there are other measures of contact frequency between HCPs and patients. For example, high radio frequency wearable devices provide reliable, high-spatial resolution contact data in real time.[22, 23]

Advantages and Disadvantage of Using EHR Data

The analysis of the study EHR pilot data has provided insights about the unit daily unique prevalence of patients with ABROs and transmission risk factors. The variance in the ABR infection transmission risk factors may serve as evidence of the unit dynamic environment. The use of EHR data may have some limitations. The issues with data in EHR can be categorized into five general areas: missing data, erroneous data, uninterpretable data, inconsistent data among providers and over time, and data stored in un-coded text notes.[183] The absence of certain data fields can also limit the outcomes to be used. It should be noted that “disease onset” is rarely captured within an EHR. As a result, varying reliability and granularity of data in EHRs may contribute to reliability of data and estimates.[184] EHR data provides several benefits. The continued production of feedback to healthcare teams using EHR data will highlight documentation issues and encourage better documentation. Using electronic data decreases the burden of data collection and provides ability to track different outcomes and measures longitudinally over the range of a particular patient’s receipt of health services. In addition, a need to follow patients across settings and institutions creates a demand for clinical applications that can be linked together to provide a complete picture of episodes of care.

4.5. Summary

Integration and representation of the necessary data with an ABRITSA graphical interface may reduce information-processing requirements.

Mapping the epidemiological information about individuals (carriage of ABRO and antibiotic use) and their locations in the hospital may support the users situational awareness about subjects at risk of “Exposure”. This concept necessitates utilization of data on “Location”. Analysis of disease **spatial**

distribution (incidence and/or prevalence) and patterns are used frequently within epidemiologic studies for mapping transmission hotspots.[149-151] The spatially-linked “MIS” may support healthcare practitioners’ situational awareness and enable tactic or strategy development.

Key Points

1. Surveillance of infection transmission risk factors should become an integral part of surveillance at a delivery group level for tracking disease burden. **Prevalence** may be a useful measure for planning resources necessary to satisfy the infection prevention and control practice demands in a specific population.
2. The important structural properties influencing the spread of infections are the arrangement of infectious contacts among the members of the population, the clustering of contacts, and the repetitiveness of contacts. Therefore, the objective of **enhanced surveillance** at the hospital unit level would be detecting spatial distribution of the colonized patients and risk factors predisposing to ABR infection transmission.
3. In hospital settings, individuals with few contacts tend to have disproportionately high levels of **repetitive contacts** with HCPs. The contaminated hands of health care practitioners are the most studied risk factor of infection transmission in hospital settings. Some individuals, particularly nurses and nursing assistants, who experience a high number of contacts, contact duration and repetitiveness, can be considered as potential **super-spreaders** of infection.
4. By integrating the surrogate and proxy measurements of infection **disease burden** and **infection prevention activity**, one may extract information and gain insight on the **patterns of actions associated with specific disease burden**. The integration of quality measurements in the infection prevention context may help HCPs quickly recognize high risk for infection transmission situations.
5. Obtaining reliable **data on proximity and contacts** between individuals may be a challenge.
6. EHR systems represent a valuable source of latent data for improving situational awareness. These data needs to be extracted and presented along with the biosurveillance data in a format that would effectively support HCP’s SA.
7. By combining spatial and temporal data, health events, occupational hazards, environmental exposures, and preventive or therapeutic services, a designer of the GUI can enrich the context for

improving user's situational awareness about transmission hotspots, individuals at high risk of exposure to ABROs, super-spreaders, and super-hosts.

Chapter 5 will addresses Aim #2: To develop the graphical features for empirical information data set, driven by the model's concepts, which would facilitate the user immediate understanding of the common operating picture. Chapter 5 provides an overview of the semiotics of graphics and image theory, from which the investigator learned about (1) attributes of efficient graphical design, (2) importance of visual variables in the visual perception, and (3) the method for constructing graphics for information communication. Then, Chapter 5 describes the application of these methods for transcribing the ABRITSA informational set into a graphical image. The main output of this chapter is the availability of the graphical image of the ABRITSA information.

CHAPTER 5: APPLYING THE RULES OF IMAGE CONSTRUCTION TO VISUALIZATION OF THE ABRITSA INFORMATION AS GROUNDWORK FOR A NOVEL GRAPHICAL USER INTERFACE DESIGN FACILITATING TACTICAL BIOSURVEILLANCE

5.1. Introduction

In Chapter 3 and Chapter 4, the investigator formalized the knowledge of epidemiology of nosocomial infections in a form of the ABRITSA conceptual model. In addition, the investigator acquired the implicit knowledge of daily variations in the unit specific epidemiological risk factors using the empirical biosurveillance and clinical data from the EHR system. Specifically, the investigator developed the understanding of the unit dynamic environment linked to the unit daily variance in volume (census) of (a) patients colonized with ABROs (I-C+), (b) patients receiving IV antibiotics (I+C-), (c) patients colonized with ABROs and receiving IV antibiotics (IC+), (d) patients requiring maximum assistance (HC+), and (e) patients lacking chlorhexidine bathing. This understanding was an important part in a design process.

Chapter 5 addresses Aim #2: To develop the user interface graphical features for the conceptual model's empirical information data set to facilitate the user immediate understanding of the common operating picture. Availability of graphics that support users' cognitive functions, such as perception of the infection transmission risks (Level 1 SA) and a comprehension of these risks (Level 2 SA), may facilitate a higher performance and better patient outcomes. The investigator sets a goal for the graphical interface design which is to enable the healthcare practitioners and staff to gain a high level of understanding about the high-risk ABRIT situations (Level 2 SA) quickly.

In an attempt to develop the efficient graphic, the investigator applied the rules for image construction to furnish large amount of the electronic health record epidemiological data into a single image that would reduce informational overload. The graphical image should yield a shared mental picture and enhance clinical sense making about ABR hazardous locations, changing infection transmission risks,

individuals at highest risk of exposure to ABRO, and “super-spreaders”. The study graphical model should answer the question “At a given location, what are the risks of infection transmission there?” in an instant of vision.

5.2. Background: Effects of Data Representation on Human Performance

Ineffective data representation in electronic health records creates problems resulting in cognitive complexity.[42-46] Cognitive complexity is defined as activities related to identifying, perceiving, remembering, judging, reasoning, deciding, and planning.[41] In spite of years of research on human-computer interface, there is a great need to manage the information effectively in order to enable healthcare practitioners to gain a high level of understanding quickly. Representing information as a graphic is a form of information processing where a vast amount of data can be reduced to understandable and memorable information.[185] Understanding of the graphically presented information can result in visual memorization, but there are the conditions of memorization; as the number of images and the amount of information increase, memorization becomes difficult. Cognitive psychology found that holding more than seven items in short memory is very difficult.[186] Thus, effectively presented data will enable humans to interpret vast amounts of data, while ineffective data representation needs to be resolved. A rapid increase of the amount of electronic healthcare data has led to an urgent need for effective representation of that data in operational settings.

A landmark study, investigating memory for photographs, found that the performance on the recognition of 2,560 pictures, each of which was displayed for 10 seconds, exceeded 90 percent.[187] In healthcare, earlier studies explored that metaphor graphic offers a new form of medical knowledge representation.[186, 188] Metaphor graphic has been defined as assemblies of icons for graphical representation of symptoms, signs, pathological situations, and some components of diagnoses. A randomized trial on the effects of text, table, pie chart, and icon on the efficiency of subjects' assimilation of information identified that icons were superior to the other graphical formats in speed ($p\text{-value} < 0.001$) and accuracy ($p\text{-value}=0.02$).[189] The researchers concluded that icons are valuable representation of

medical information. Other studies found the icon-based graphics were more effective than numerical formats in increasing risk-avoidant behaviors in patients.[190-193]

Epidemiological data can be visualized with tables, graphs, and maps. Depicting surveillance data with maps has long been a standard approach to illustrate geographic clustering and regional differences in disease prevalence or incidence. By combining geographical data on health events with the location of hazards, environmental exposures, or preventive or therapeutic services, a geographic information system can facilitate the study of spatial associations between exposures or services and health outcomes in different locations.[73] Graphical structures like maps immediately communicate essential points or critical cues.

The use of map of enclosed healthcare facilities as a method for improving situational awareness for clinical management is a novel concept. The following literature review is important for understanding how maps can furnish large data sets and improve efficiency in information communication.

5.3. Image Theory

Jacques Bertin, a French cartographer and theorist in the field of information visualization, described *graphic representation* as a sign-system invented for the purposes of storing, understanding, and communicating essential information. He states: “*Graphics owes its special significance to its double function as a storage mechanism and a research instrument.*” The main purpose of the graphic is to “better understand the data by transforming the data”. To enable users’ better perception and understanding of information, designers process the data with graphics, using maps, tables, or networks. Transcribing data into graphics is a form of information processing. In addition, graphics often serve as artificial memory.

Experimental psychology explains that human visual perception interacts with the ability to understand and memorize the forms within an image.[185] The matrix theory of graphics is the application of this property of visual perception. Bertin defines image as a meaningful three independent dimensions (X, Y, and Z) visual form, perceptible in the minimum instant of vision.

The graphic systems utilize visible marks, including a point, a line, and an area. The visible marks can be represented with eight visual variables. The first two variables are the two dimensions of a plane (X and Y) because the marks can vary its positions in relation to X- and Y-axes. The marks also vary in Z-axis. While, the eye perceives two orthogonal dimensions of the image X and Y, a variation in light energy produces a third dimension in Z. In order to construct an image and to permit understanding of that image, the designer utilizes retinal variables to represent a variable Z, including (a) size, (b) value, (c) texture, (d) color, (e) orientation, and (f) shape or symbol. These six retinal variables graphically represent a **qualitative variation between the objects** and “elevate” Z component above the plane.

The plane enables the designer to construct diagrams, networks, maps, and symbols. Diagram represents a graphic construction for the correspondences among all the elements of one component (X) and all the elements of another component (Y) on the plane. Network represents a graphic construction for the correspondences among all the elements of the same component. Geographic map represents a graphic construction for the correspondences among the same geographic component, inscribed on the plane according to the observed geographic distribution. Symbols or figurative analogies (e.g., icons) represent a graphic construction for the correspondences on the plane between a single element and the user. While diagrams show the relationships among characteristics, networks and maps show the relationships among objects.

To choose right graphic formula for a set of information, the designer should identify the purpose of graphics, consider the number of concepts, and the presence of a geographic component and then determine the most efficient image construction.

5.4. The Eye Physiology and Information Perception

Efficiency of the image is defined as “the most efficient construction that enables a person to answer any question in a single instant of perception.”[185] When one construction requires a shorter observation time (Time) than another construction to answer a given question, this construction is more efficient. Efficient graphics also facilitate inscribing the information into visual memory (Memory). Thus, the primary graphical problem encountered is identifying the best degree of data simplification that would

provide enough information for decision-making with minimum cognitive load and optimal time. This problem links to issues of visual selectivity and conceptual complexity of a graphic, which appear when each additional component transcribed into a graphic increases the conceptual complexity and visual variability, leading to an increase in Time, and decreases memorability of the graphic.

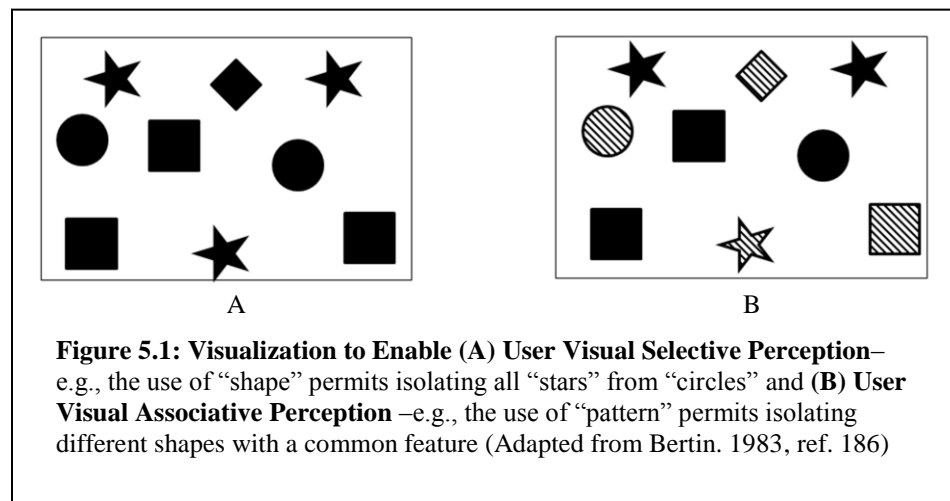
A graphic can furnish the means of retaining information with the help of visual memory. The knowledge of eye physiology explains what makes visual perception instant or non-instant. The X and Y components introduce a meaning that transforms the plane into quantities, categories, time, or space (in maps). According to Bertin, the user perceives the planar dimensions through the intermediary of eye movement, so-called “muscular response”. In contrast, the retinal variables, inscribed "above" the plane, are independent of it. The eye perceives the retinal variation without eye movement.

The retinal perception is called retinal response. Bertin emphasizes that the retinal variables are physiologically different from the planar dimensions. The plane and retinal variables have specific perceptual properties. While the plane possesses all perceptual properties, including selective, associative, ordered and quantitative properties, the retinal variables hold only some of these properties. Bertin explains that any individual can **immediately classify** a series of values, ranging from black to white. The value variation from white to black can be used to represent an ordered concept (component) and provide an immediate visual response for any question by implying an ordered perceptual approach. In contrast, a shape variation (e.g., star, circle, triangle, etc.) cannot represent an ordered concept (component) and thus cause an immediate visual response.

In order to choose the most efficient **retinal variables**, it is important to determine the level of organization of each concept (graphic component/variable) and the length of each concept. The experimental psychology of binocular vision identified the factors affecting depth perception, including a decrease in the size of a known object, a decrease in the values of a known contrast, a reduction in the known texture of an object, a decrease in the saturation of the colors of known objects, and deformations of orientation and shape.[194] Transcribing a set of information into an efficient three-component image depends on the application of these factors that enable human (1) associative, (2) selective, (3) ordered, or (4) quantitative visual perception.

Associative Perception

When the user needs to quickly associate (combine) two different components, the retinal variables need to facilitate “associativity” or “equalization”. Associative perception can be achieved with the use of texture, shape, and orientation. (Figure 5.1 A). In contrast, a variation in value (black-gray-white) or size variations are not associative; they are dissociative because they prohibit carrying out an immediate visual selection for the other variables. Associativity of a retinal variable can be judged how quickly the eye can reconstruct (reestablish) the uniformity of the area, despite a given visual variation.



Selective Perception

When the user needs to quickly isolate all the correspondences belonging to the same category (element) of one variable (concept), the retinal variables should allow these correspondences to form “a family” (Figure 5.1 B). Color, texture, and a mark position can enable selectivity; for example, the family of black signs or white signs, the family of signs on the right or on the left position of the plane. The user can disregard all the other signs and perceive the image formed only by the given category if he can easily juxtapose (compare and contrast) separate images on the plane. In order to facilitate the immediate selective perception, the retinal variable should enable the eye to form a family of objects instantaneously to answering the question: “Where is a given category?” If the perception can necessitate going through sign by sign, the variable does not enable selectivity.

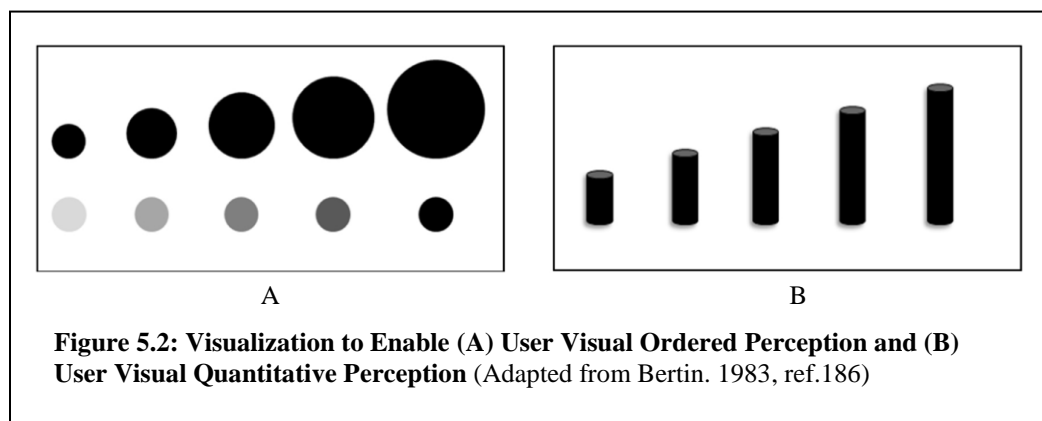
Ordered Perception

When the user needs to compare two or several orders, the retinal variables should facilitate the ordered perception. The retinal variables that can “create” an order that is universal and immediately perceptible include texture, value, and size (Figure 5.2 A). All three types of marks, such as a point, a line, or an area, can be presented with texture, value, and size, and thus facilitate a user’s ordered perception. In contrast, the shape, the orientation, and the color (value excluded) are not ordered. If a comparison is immediate, the variable is ordered, and it is not necessary to refer to the legend. The best test is to ask the user whether he can immediately reestablish the universal order of the signs for each variable.

Quantitative Perception

Quantitative perception is involved when one numerically defines the ratio between two signs; it appears immediately to the user that this is double that or is eight times that. Only size variation (Figure 5.2 B) allows quantitative perception, while value and texture variation do not. Quantitative perception represents an accurate approximation, but not a precise measurement.

No single retinal variable possesses all four perceptual properties. The hierarchy of the visual variables that permit selectivity starts with the use of size and value, as the top choice, followed with color, texture, and orientation. This sequence affects the choice of a graphic representation. Shape has no selectivity; however, it provides a base for symbolism. Selectivity is also applied when characteristics are superimposed (overlaid). The utilization of retinal variables for representation of the ordered qualitative components is the basis for graphic information processing. Suitable graphical ordering simplifies the images without diminishing the number of observed correspondences and changing the meaning.

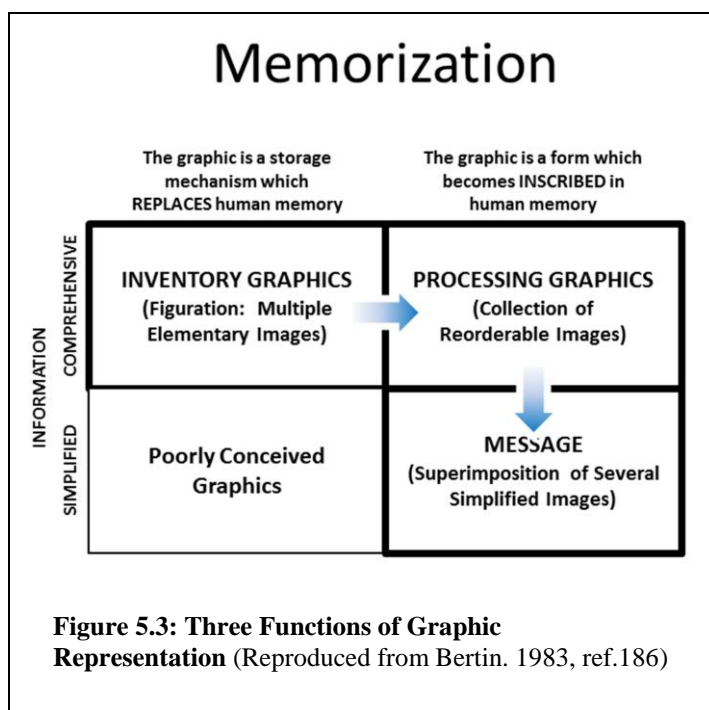


5.5. Three Functions of Graphic Representation

The simplification of complex information involves knowledge of the functions of graphic representation. Graphics have three primary functions: (1) inventory-recording information, (2) message-communicating information, and (3) memory-processing information (Figure 5.3). When a graphic serves as a comprehensive inventory of information, it authorizes the construction of complex figurations with multiple images. The examples include a subway map, an airport map, a city map, and others. The main goal of such inventory is to display comprehensive information with numbers, letters, shapes, or colored symbols in a table or a map format. Information represented in this way is the first state in communication.[185] The inventory-type graphics serve a role of an artificial memory, allowing the user to avoid memorizing the information.

Furthermore, a graphic can furnish the means of retaining information with the help of visual memory. Reducing the number of correspondences and keeping essential ones can simplify the *information conceptual complexity* (e.g., a school map). The process of **elimination of some information** makes the image less comprehensive but easier for inscribing information in the viewer's memory. Such image can be recalled when needed. In this case, the graphics serve a memorable "message" role. Reduction in both the number of images and the image complexity leads to an increase in the graphics efficiency. A set of information can be graphically represented with a comprehensive and memorable image when this information is processed with the mechanism of **ordering and classing** for the purposes of discovering the groupings.

The mechanism of ordering and classing is different from the mechanism of elimination of part of the information. Visual ordering and classing create new categories (components). New categories should reduce the number of the overall categories and make the image memorable and comprehensive. The new components or subsets of information increase the speed of comprehension and lead to better "communication". Graphic simplification is not always necessary for information including one to three components; the eye itself can simplify the image to the necessary level. **Superimposing** several images in a figuration is an additional method of information reduction or simplification.



An image, such as a diagram or a map, is intended to be “questioned”. Graphics can generate questions for all three dimensions X, Y, and Z. Bertin states that there are three basic questions that constitute the basis of the matrix theory.[185] These three questions are applicable to any problem and can be used to assess the usefulness of any graphic innovation: (1) What are the X, Y, Z components? (2) What groups are formed by the data in X and Y? or What groups in X and Y are formed by the Z? and (3) What are the exceptions?

The Application of Matrix Theory to Cartography

If a set of information involves a geographic component, a map is a useful construction. A map is a single image that occupies the two planar dimensions (two components) X and Y. Any problem involving more than two components leads to a greater number of images. Three-component information can be constructed as several images or as a figuration composed of multiple images. Matrix theory enables a user to read a map and define the two most pertinent questions: “What is at a given place?” and “Where is a given phenomenon?” Maps can show one phenomenon or display several phenomena. Mapping introduces geographic order and enables visual memorization and comparison. The construction of a map is simple but time-consuming; it includes reproducing the geographic order and recording the given correspondences. A

geographic network cannot be reordered arbitrarily. Therefore, the map-based image can only be simplified by eliminating certain correspondences.

Bertin explains if the information has two components, its graphic representation necessitates *three variables*: two planar dimensions for the geographic order (X and Y), and a visual variable for the third component (Z).[185] Also, the third component necessitates the use of visual variables that enable ordered perception. Information constructed according to this rule will be perceptible as a single image. If a graphic representation has to represent a four- or more component information set, then the designer has to choose among the following:

Inventory map: a comprehensive image that must be read point by point;

Processing map: a collection of images, which represent the comprehensive information on separate maps that are comparable and classable; or

A cartographic message or synthetic scheme: when several simplified images representing the essential concepts or elements of information are superimposed.

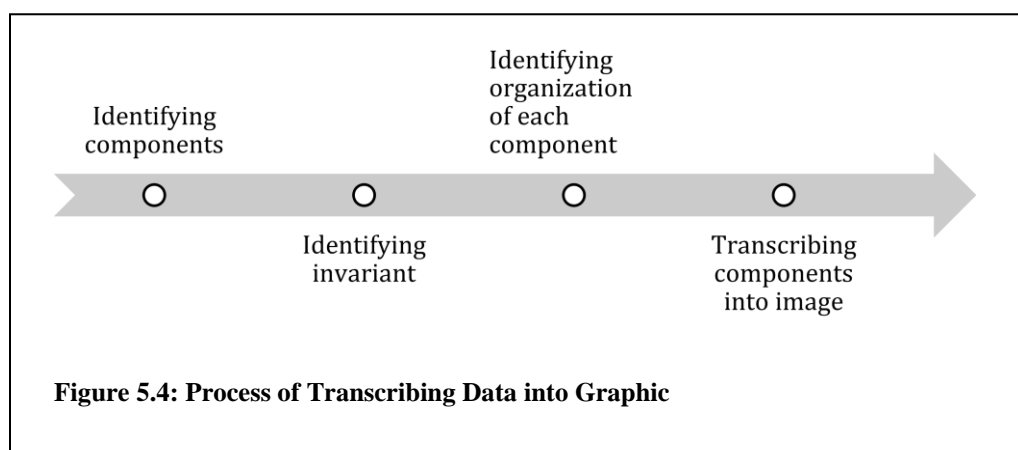
The **superimposing** of the several images, the additional method of information reduction or simplification, can also be accomplished with a map. The geographic images should be simple and limited in number. Maps also allow the user to answer three basic questions in relationship to the geographic order. The first question asks about the meaning of the X,Y, and Z dimensions. This question helps the user to understand what the map is. The map must also provide the answers to the questions (1) pertaining to Y, such as “A given characteristic, where is it?” and (2) pertaining to X, such as “At a given place, what is there?” The other two basic questions include “What are the groups?” and “What are the exceptions?” These questions also help to assess the usefulness of the map.

5.6. The Rules of Graphic Construction

Bertin defines “a thought” as “a relationship among various concepts that have been recognized and isolated at a given moment from among the multitude of imaginable concepts”. In graphic representation, the content of a thought is called the information and is formed by one or an infinite set of

variational concepts (components). To construct images, the first step involves analysis of the transcribed information, identifying the information components and a component which serves as *invariant*. The second step involves identifying the number of elements in each component (length of the component) and the level of organization of each component (Figure 5.4). The last step involves transcribing the information set into image by choosing particular planar and visual variables.

The information can be perceived as a single image where three components are transcribed. According to Bertin, a person can normally perceive an image with three components X, Y, and Z and rarely seven components.



Invariant

One component can become common to all the data; this component is called the invariant (e.g., a geographic order). The variational concepts are called the components (e.g., time-variation of the date, quantity variation of the people, risk, etc.). The examples of invariants include a defined geographic space for epidemiological studies, a group of individuals for a survey, the period for historical research, and others.

Number and Levels of Components

Each component can have different levels characterized as qualitative (nominal), ordered, and quantitative levels. The first level of a component is qualitative or nominal, when the component's

elements can be reordered arbitrarily for purposes of information processing. The qualitative (nominal) level includes all the innumerable concepts of simple differentiation, for example, diseases, patient epidemiologic states (colonized vs. not colonized), and antibiotic intake (intake vs. no intake). The second level of a component is achieved when the component's elements can be ordered and re-ordered in a single and universal manner. Ordered components can be defined in relation to a temporal order (e.g., age, period from the time of onset of antibiotic resistance), a sensory discrimination order (black, gray, white; large, medium, small; here, near, far), a disease severity order (severe, moderate, mild), and other. Geographic groupings are also re-orderable; geographic areas can be categorized by mortality rate, infection density, utilization of antibiotics, level of infection prevention activities, and other. The third level (quantitative) is attained with the use of countable units leading the user (user) to compare numerical differences. Qualitative vs. quantitative data necessitate the use of two different graphical structures: Network (map) vs. Diagram. The quantitative components necessitate the use of Diagram. Most qualitative components are represented with the individual level data that can be visualized with the use of retinal variables, such as *color, size, texture, symbols, and shape*.

Length of the Component and Graphic Processing of Information

Components are divisible and can have a different number of elements or divisions. The number of elements determines the length of a component. "Short" components are those with a length of up to four divisions. Short components simplify visual variability. "Long" components have more than fifteen divisions. For continuous data, the term "length" is not applicable, instead, a range of values serves as the length.

Transcribing Information into Graphics

In order to produce the efficient image, the retinal variables have to match the length, which is determined by the number of component divisions, they represent. When the levels of components and visual variables correspond with each other, then a diagram or a map becomes visually retainable furnishing only one immediately perceived image. The complexity of the image depends on the number of elements (divisions) in each component. The components with numerous elements create a challenge for graphical representation. The visual variables representing each component must also permit corresponding

perceptual approaches, including visual selectivity, associativity, and ordering. Visual perception is important for comparing characteristics, discovering similarities and differences, and identifying areas of interest or exceptions (exclusions).

The number of components determines the number of questions. Questions need to be categorized by levels of reading, such as the elementary level, intermediate level, and overall (total) level. The elementary level of reading includes questions introduced by a single element (division) of the component. The intermediate level of reading includes questions introduced by a group of elements of the component. The overall level of reading includes a question introduced by the whole component. Mapped data (map) can provide instantaneous answers, making the groups, exceptions, and potential explanations appear. The guiding principles for the image construction and techniques for reducing the informational complexity are summarized in Table 5.1.

Table 5.1: Guiding Principles for the Memorable Image Construction

Information Conceptual Complexity	Information Reduction (Simplification) Methods	Methods for Improving Information Perception
A person can normally perceive an image with three ($n=3$) components XYZ, rarely seven ($n=7$) components.	<ol style="list-style-type: none"> 1. <i>Elimination</i> of certain correspondences; 2. "<i>Superimposition</i>" of several images in a figuration; 3. <i>A four-divisions or less component</i> simplifies visual variability. 	<ol style="list-style-type: none"> 1. The levels of components and the levels of visual variables should correspond with each other; 2. Visual variables should permit "<i>selectivity</i>"; 3. The hierarchy of the visual variables that permit selectivity starts with the use of <i>size</i> and <i>value</i>, followed with <i>color</i>, <i>texture</i>, and <i>orientation</i>; 4. <i>Superimposition</i> of components permits visual selectivity.

5.7. Study Design and Methods

In order to develop efficient graphical features for the conceptual model's information set that support user's situational awareness, the investigator applied the Rules of Image Construction, grounded into Matrix Theory and the knowledge about physiology of a retinal perception.

It was hypothesized that a map, as a graphical structure, would enable the designer to reduce the conceptual complexity of the infection transmission informational model. A physical layout of the study

medical-surgical unit would serve as an archetype of map. The pertinent questions of this qualitative case study were:

- To what extent can the 50-bed medical-surgical unit population ABRITSA information be graphically reduced?
- What is a meaningful minimum of information to be retained?
- What methods of information simplification can be used?

Rationale: We can take advantage of human visual perceptual means if we graphically present the ABRITSA concepts, correspondences, and the relationships among objects. The presence of a spatial concept in the ABRITSA model, such as *proximity to a source of infection*, and spatially linked concepts related to infection transmission informs the researcher that the most useful construction form is a **map**. The important elements “proximity” and “exposure” can be instantaneously identified when a map represents infectious agent, member infection state, risk of infection transmission (bacterial load), and receipt of infection intervention .

This qualitative case study employed Bertin’s method of image construction including the following steps:

The image construction methodology:

1. Determine a purpose of the ABRITSA information visualization;
2. Conduct the Component Analysis to assess the complexity of a figure;
3. Identify suitable retinal variables for the model components and determine the corresponding levels of these variables;
4. Apply the graphical methods for reducing informational complexity of the image (e.g., the superimposition of simple images on the map);
5. Construct the graphic(s).

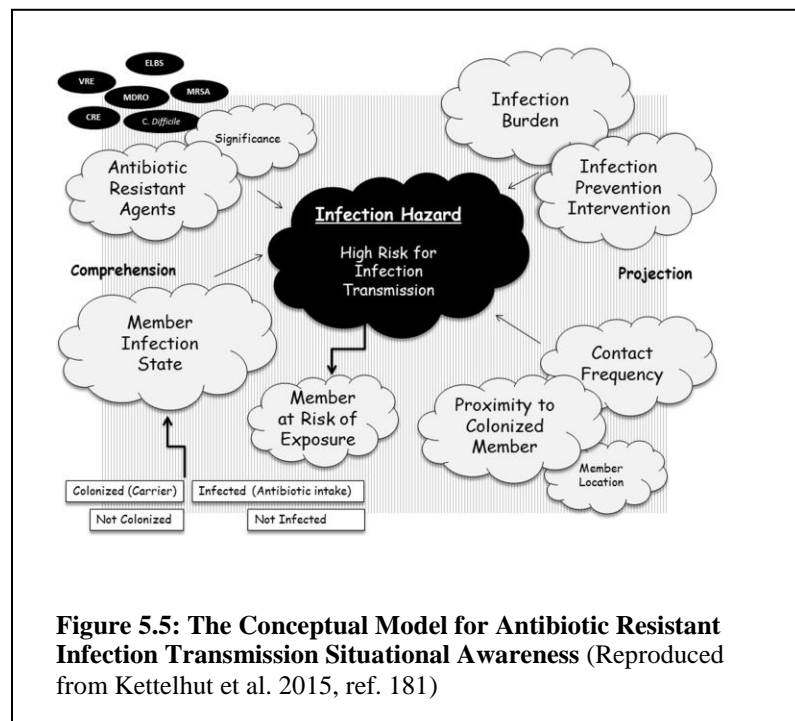
The expected outputs of this case study were:

1. An experimental image of the ABRITSA model features (visual artifacts);

2. An understanding of the rules of image construction and techniques for reducing the healthcare information complexity (e.g., elimination of certain correspondences, processing information by ordering and classing, and superimposition of the images) as a method for developing novel visualizations of healthcare information;
3. A descriptive summary of the graphic formula; and
4. A conceived set of drawings as a demonstrational unit.
5. The significance of this research is its unique focus on developing the graphics that provide cognitive support for user's perception of the infection transmission risks (Level 1 SA) and comprehension of these risks (Level 2 SA).

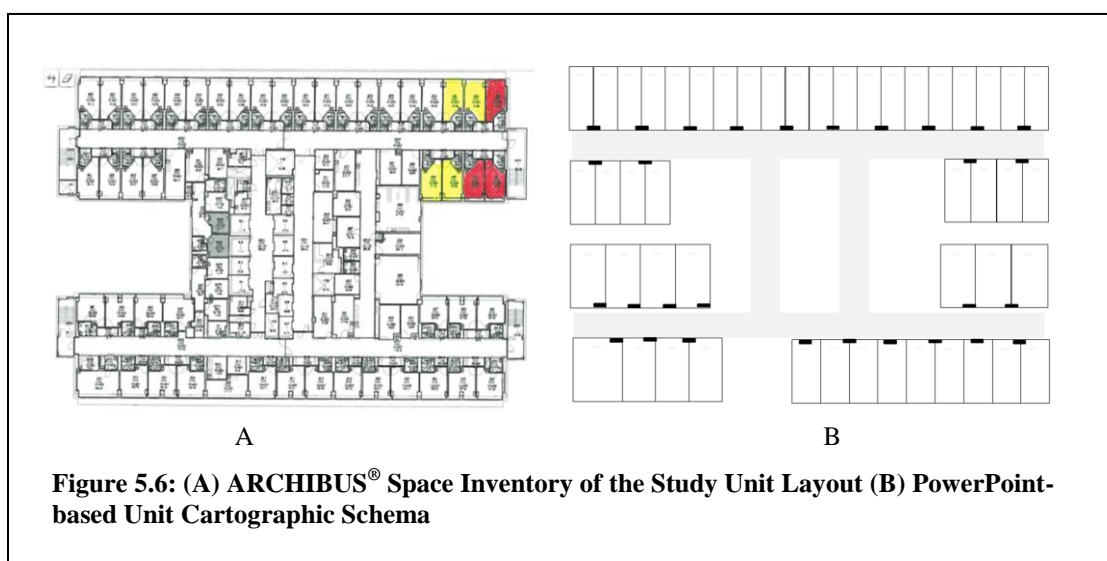
5.8. Transcribing the ABRITSA Information Set into Graphics

Figure 5.3 provides a pictorial framework of the ABRITSA concepts developed in Chapter 3 and Chapter 4 for the infection control domain. This framework directed the development of the user's interface graphic design described further.



Step 1: Obtaining the Medical-Surgical Unit Physical Layout

The investigator started the process of image construction with building a map of the enclosed environment. For this, the investigator obtained an architectural map of the medical-surgical unit from the hospital space planning and management department. The hospital floor plan (Figure 5.6.A) was designed with the use of ARCHIBUS® Space inventory and performance program[195] and included all the rooms and space available in this unit. The investigator constructed a simplified version of this map with the use of the Microsoft PowerPoint and represented the unit layout, wards, and the wards' common circuits (Figure 5.6.B).



Step 2: Determining the Purpose of the ABRITSA Graphic(s) as a Groundwork for the Graphical User Interface

An important step in developing a visualization of health data was to determine its purpose. The purpose of the ABRITSA information visualization is to enable healthcare practitioners to gain a high level of understanding about the high-risk ABR infection transmission situations (Level 2 SA) quickly. Specifically, the graphical representation of the ABRITSA information should address relevant to the domain questions: e.g.

- “At a given place, what is the risk of infection transmission?”
- “At a given place, who is at a greater risk of exposure to ABR infections?”

The investigator specified a goal and several short-term and long-term functional requirements the GUI has to employ (Table 5.2).

Table 5.2: Goals and Functional Requirements for the Enhanced Biosurveillance GUI

GOAL: To enable the recognition of infection transmission pattern and trends for tactical decision-making aiming at patient and public health safety
Reduce users' needs for processing of enhanced biosurveillance information.
Minimize users' time for acknowledging spatial characteristics or locations of the infection transmission risks.
Eliminate users' needs for searching critical information in the latent EHR text and non-text documents for infection transmission and exposure events.
Enable users' instantaneous perception of the critical cues for infection transmission (Level 1 Situational Awareness) by taking advantage of visual perception and visual memorization. Ultimately, facilitate users' comprehension (Level 2 Situational Awareness) by providing the explicit visual signals on high risk for infection transmission areas (transmission hotspots) and subjects at high risk of exposure (super-spreaders and super-hosts).

Step 3: The Component Analysis for Assessing the Complexity of a Figure

The next step was the analysis of the informational content of the conceptual model. Bertin explains that data represents *content* while a graphic serves the role of a *container* for these data and represents the properties of the graphic system. The informational “*content*” in this study was developed in Chapter 3 and Chapter 4.

In the preliminary work, the content, formalized as the ABRITSA model, included 15 concepts, representing the critical cues for identifying the implicit cognitive concepts, such as *transmission hotspots*, *subjects at high risk of exposure*, and *super-spreaders*. The model's concepts include (1) infectious agent, (2) member susceptibility state, (3) member infection state, (4) location, (5) common circuit, (5') contaminated circuit, (6) receipt of infection prevention intervention, (7) conformance: infection prevention performance, (8) contradiction to infection prevention intervention, (9) unit infection burden, (10) source location, (11) exposure (proximity to source), (12) high contact patient (intensity of exposure), (13)

duration of exposure, (14) hazard zone: risk of infection transmission (bacterial load); and (15) unit density of infection.

Step 3.1: Defining the Number of Components and Invariant in the Data Set

Following the rules of image construction, the investigator analyzed the ABRITSA information set and determined components and invariant for the graphic, the components' names, the level and type of data, and potential type of images (Table 5.3). Bertin defined the **invariant** as a component that is common to all the data. In this study, the hospital unit spatial (geographic) order becomes the invariant. The spatial element is the ward of the unit, which is a distinct geographic space representing variation of the locations. The invariant takes two components X and Y to represent a layout of a 50-bed medical-surgical unit. The analysis necessitated reiteration of the drawings of the components for developing preliminary understanding of type of images applicable for each component. This iterative process helped to sort out the components for Level 1 SA vs. Level 2 SA. The Level 1 SA components included: agent, members, locations, disease burden, and infection prevention intervention. The Level 1 SA components included: agent, members, locations, disease burden, and infection prevention intervention. The Level 2 SA components included: transmission risk and exposure (Table 5.3).

Then, the investigator identified the presence of the qualitative (nominal) and quantitative (continuous) types of data to determine the use of two different graphical structures, Map and Diagrams.

The next step in the conceptual design process was the creation of the visual artifacts for the components. The investigator continued the analysis of the qualitative components: (1) infectious agent, (2) member infection state, (3) geographic location (ward number), (4) potentially contaminated common circuit, (5) receipt of the infection prevention intervention, (6) contraindication(s) to infection prevention intervention, (7) hazard zone, (8) significance of risk of transmission (concentration of agent). Following the rules of image construction, the investigator determined the second component, the “common circuit”—a common area where the doors of two wards open out. This component included two elements: “contaminated circuit” and “non-contaminated circuit”. Contaminated circuit is a “cue” indicating a potential contamination of the circuit with ABRO(s) when one of the adjacent wards is occupied by a carrier of ABRO. Then, the investigator performed the same component analysis for the rest of the

qualitative components. After a series of reviews, it was decided to keep the **ten essential components** that contribute to the implicit cognitive concept “transmission hotspot” and are critical determinants of the concept “individual at high risk of exposure to ABRO” (Table 5.4 A).

Table 5.3: Translation of Concepts’ Names into Image Components’ Names

<i>CONCEPT</i>	<i>COMPONENT</i>	<i>COMPONENT NAME FOR VISUALIZATION (STUDY COMPONENTS)</i>	<i>LEVEL OF DATA</i>	<i>TYPE OF DATA</i>	<i>TYPE OF IMAGE REQUIRED</i>
Agent					
<i>AGENT</i>	Infectious Agent	Infectious agent name	Individual	Qualitative	Symbol, text
Members					
<i>PATIENT</i>	Member Infection State	Colonized Infected	Individual	Qualitative	Color, texture
<i>PATIENT</i>	Susceptibility state	Susceptibility	Individual	Qualitative	N/A
Location					
<i>LOCATION</i>	Location (ward number, bed number)	Ward number	Individual	Qualitative	Map
<i>LOCATION</i>	Common circuit	Common circuit	Individual	Qualitative	Shape
<i>LOCATION</i>	Potentially contaminated common circuit	Contaminated circuit	Individual	Qualitative	Color
Disease Burden					
<i>DISEASE BURDEN</i>	Prevalence of colonized patients: a proportion of the colonized patients on a unit	Daily variation in unit colonization pressure	Aggregate	Quantitative	Diagram
<i>DISEASE BURDEN</i>	Antibiotic utilization	Daily variation in unit use of antibiotics	Aggregate	Quantitative	Diagram
Intervention					
<i>INTERVENTION</i>	Receipt of the infection prevention intervention	No Chlorhexidine bathing	Individual	Qualitative	Shape, color
<i>INTERVENTION</i>	Contraindication(s) to infection prevention intervention	Allergy/intolerance to chlorhexidine products	Individual	Qualitative	Shape, color
<i>INTERVENTION</i>	Compliance: infection prevention performance	Daily variation in unit compliance with chlorhexidine bathing	Aggregate	Quantitative	Diagram
Likelihood of Transmission					
<i>LOCATION</i>	Hazard Zone (location of a colonized patient)	Hazard zone: infection transmission	Individual	Qualitative	Symbol, color
<i>RISK</i>	Risk of transmission (bacterial load-time of onset)	Risk of transmission	Individual	Qualitative	Size, color
<i>EXPOSURE</i>	Intensity of exposure	High contact patient	Individual	Qualitative	Shape, color
<i>EXPOSURE</i>	At risk of exposure	Proximity to the hazard zone	Individual	Qualitative	correspondence
<i>EXPOSURE</i>	Dose of exposure: duration of being at risk of exposure	Dose of exposure: duration of being Exposed	Individual longitudinal	Quantitative	Diagram

Then, the investigator had to determine the most efficient visual images for each component. This task required identification of the level of retinal variables and selection of those variables that permit

visual perceptual selectivity and associativity and reduction in the conceptual complexity. By drawing different sketches and experimenting with the different visual variables and techniques for visual data processing (classing, ordering, and superimposition) the investigator tried to reduce visual variability and the conceptual complexity, permit visual selectivity and associativity, and preserve the original meaning of the ABRIT informational set. This iterative and creative work yielded a set of the visual artifacts described in Table 5.4 A and Table 5.4 B.

Table 5.4 A: Determining the Levels of Organization of Components for Reducing Conceptual Complexity and Number of Correspondences

COMPONENT	ELEMENTS OF COMPONENT	LENGTH OF COMPONENT	LEVEL OF COMPONENT	RETINAL VARIABLE	INFORMATION PROCESSING METHOD
GEOGRAPHIC LOCATION	Unit layout	2 (X, Y)	INVARIANT		Ordered network
WARD NUMBER	50	50	Qualitative	SYMBOL: TEXT	
COMMON CIRCUIT	1. Not contaminated 2. Contaminated	2	Qualitative	SHAPE Brick b/w adjacent rooms COLOR Grey Red	Classing, Ordering
INFECTIOUS AGENT	At least 8 clinically important ABRO	8	Qualitative	SYMBOL: TEXT	Superimposing
COLONIZED	1. Carrier of ABRO 2. No History of ABRO carriage	2	Qualitative	COLOR: 1. Red 2. Gray	Classing,
INFECTED	Not Infected (no receipt of antibiotics)	1	Qualitative	TEXTURE	Eliminating
(HAZARD ZONE: SIGNIFICANCE OF RISK OF INFECTION TRANSMISSION)	If “Colonized” then “Hazard Zone” 1. High Risk (< 3) 2. Moderate Risk (3-6 m) 3. Low Risk (> 6 m)	3	Qualitative	SIZE, SYMBOL 1. Large glow 2. Small glow 3. No glow	Classing, Ordering
HIGH CONTACT PATIENT	Yes (maximum assistance or dependent on external assistance)	1	Qualitative	SHAPE, COLOR Yellow dot	Ordering, Eliminating, Superimposing
RECEIPT OF INFECTION PREVENTION	No receipt	1	Qualitative	SHAPE, COLOR Red ring	Ordering, Eliminating, Superimposing
ALLERGY/INTOLERANCE TO CHLORHEXIDINE COMPONENTS	Yes	1		SHAPE, COLOR	Ordering, Eliminating, Superimposing

All components proposed for visualization with diagrams should follow the same divisions and utilize the same retinal variables to reduce the cognitive burden for the users.

Table 5.4 B: The components to be presented with diagrams

COMPONENT	ELEMENTS OF COMPONENT	LENGTH OF COMPONENT	LEVEL OF COMPONENT	GRAPHIC	RETINAL VARIABLE
COMPLIANCE: INFECTION PREVENTION PERFORMANCE	Range	Range	Continuous	Diagram	
DAILY VARIATIONS IN UNIT COLONIZATION PRESSURE	Range	Range	Continuous	Diagram	
DAILY VARIATIONS IN UNIT COLONIZATION DENSITY	Range	Range	Continuous	Diagram	
DAILY VARIATIONS IN UNIT USE OF ANTIBACTERIALS	Range	Range	Continuous	Diagram	
DATE	Continuous	Range	Continuous	Calendar	SYMBOL (text)

Findings:

”Member Infection State” permitted the creation of an independent visual component “Colonized” (a carrier of ABR) consisted of two elements (1) “C+” a carrier of ABR vs. (2) “C-” non-carrier. The least prevalent infection state “C+”, yet, the most significant for infection transmission, was visualized with the use of red color to permit visual selectivity. The most prevalent “MIS” type, such as the non-carriers “C-”, was visualized with the gray color. Each ward occupied by “C+” vs. “C-” patients was color-coded correspondingly.

The concept “Infected” originally included two elements: a receipt of antibiotics “I+” vs. no receipt “I-”. The use of a texture for the element “I-”, with a background color, red vs. gray, of the principal component “Colonized”, considered beneficial for several reasons. First, such visualization reduced visual variability by retaining the same background colors. Second, it made the most prevalent and a benign, from the infection transmission perspective, type “I-” less salient, permitting a better selectivity for the phenotype “I+”. Finally, the use of texture permitted a perceptual associativity when a user can easily associate the sub-groups “I+” or “I-” among the phenotypes “C+” and “C-”. This approach reduced the

original 4-division component “Patient Infection State” into two short components, including a two-division component for “Colonized” and a one-division component “Infected”.

The components that were spatially linked to the “Colonized” patient’s location, such as “contaminated circuit” and “hazard zone”, inherited the red color of “Colonized” patients in order to enhance the visual selectivity. The “Circuit” was represented with the use of shape, a brick, to show a common area of the adjacent wards. The “Contaminated circuit” was represented with a red-color brick while “non-contaminated circuit” was represented with the gray color brick.

The spatially linked component “Hazard zone: infection transmission” risk included the three elements to communicate the hypothetical magnitude of infection transmission risk, such as significant, moderate, and low. The use of the retinal variable depicting “size” of the risk enabled visual selectivity. “Size” naturally corresponds to the amount of bacteria and, respectively, the significance of infection transmission risk. As a result, this visualization eliminated a need to calculate this measure and increased the speed of comprehension.

The component “High Contact Patient” denotes a group of patients who require maximum assistance and, thus, experience very frequent contacts with healthcare workers. Frequent contacts increase the risk for infection transmission among members of a population. This component included one element represented with a symbol, a yellow dot. The investigator planned to superimpose this visual artifact over the patient’s location to enable an easy link to the principal component “Colonized”. The superimposing of the two components improved the perception about infection transmission area.

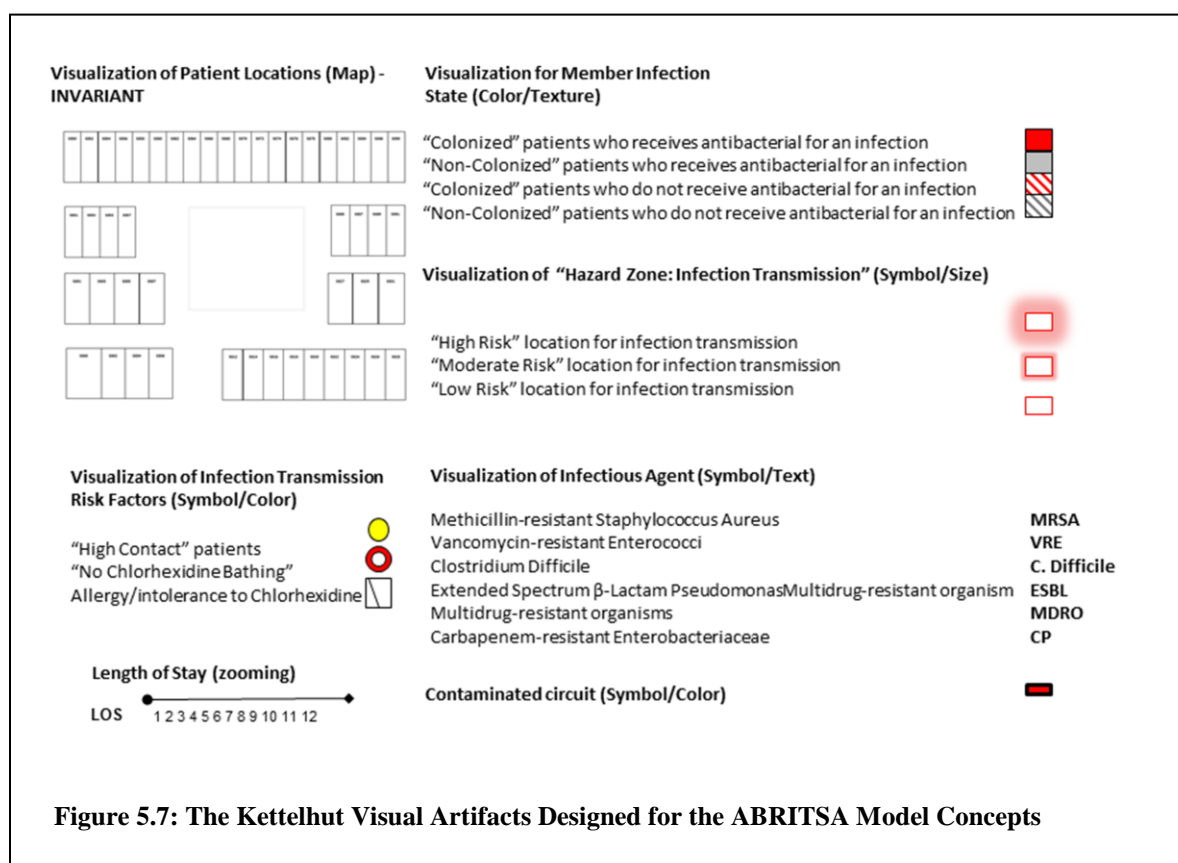
In this study, “Receipt of an infection prevention intervention” represented a receipt of chlorhexidine bathing. The investigator decided to include only one element “No receipt of chlorhexidine bathing” to inform a user about the underuse of the preventive intervention. This short component was represented with a symbol, a red circle.

The red circle “No receipt...” and the yellow dot “High contact patient” can be superimposed. This information processing mechanism permitted a visual selectivity for identifying a sub-group of patients who experienced frequent contacts and lacked infection prevention. When these two components were

superimposed on the patient's phenotype "C+", they enhanced the cue about the risk of infection transmission in particular patients.

The concept "exposure" is a complex, implicit, spatial concept facilitating users' comprehension (Level 2 SA). This concept is linked to the other implicit cognitive concepts, such as transmission hotspots, subjects at high risk of exposure, and super-spreaders. The transmission hotspot concept can be represented with one component visualized as (1) a line demarcating a cluster of the wards occupied with ABRO carriers "C+" or (2) an area visited by the super-spreaders. The super-spreader concept can be represented with a single component visualized with a symbol. These visual artifacts are secondary to the primary artifacts analyzed in this qualitative case study.

A symbol "cross line" can visualize a contraindication of chlorhexidine product. Figure 5.7 presents the visual artifacts explaining the most important ABRITSA basic concepts developed for the graphical design discussed above.



5.9. Study Outputs

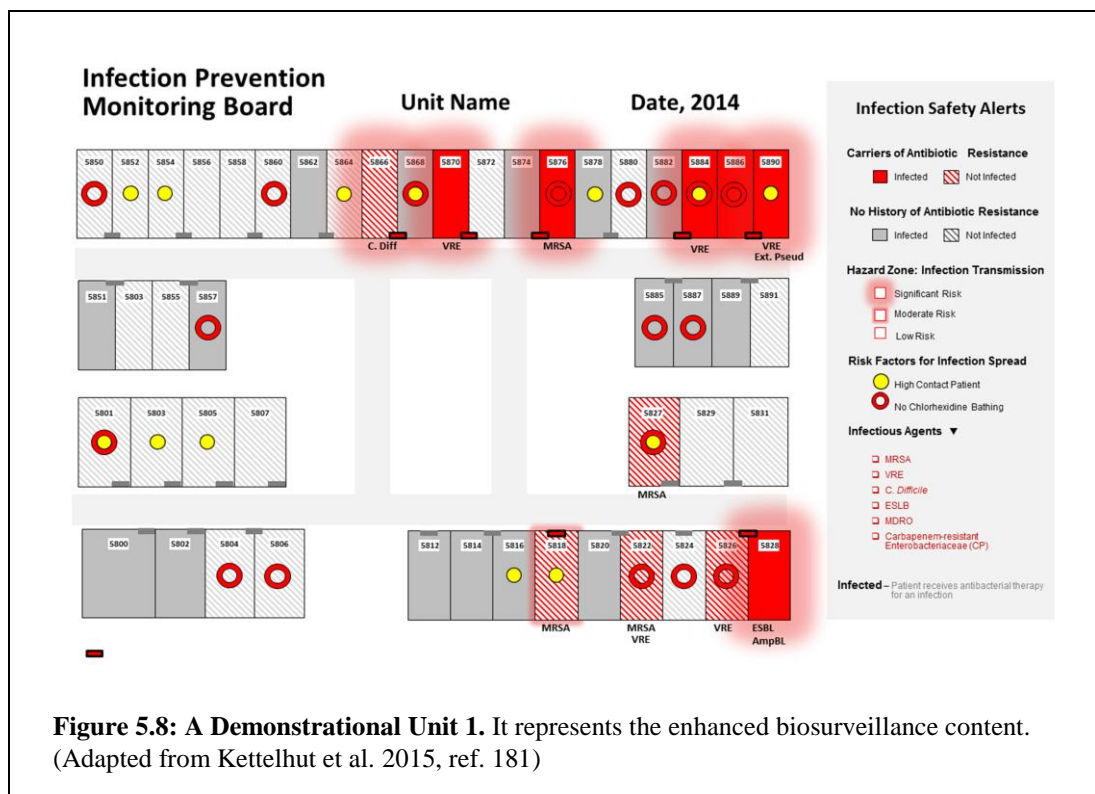
The investigator developed a series of the visual artifacts and the graphical structure to enable clinical situation sense making. The design process applied the rules of image construction to the empirical data abstracted from the EHR, comprising the content for the ABRITSA model. The graphic development included: (1) building the map; (2) analyzing the components' length (divisions); (3) drawing the sketches for the components and testing different visual variables; (4) reducing the visual variability by visually ordering some components; and (5) identifying the best visual variables to enable selectivity. The result of this qualitative study is the developed 11-component graphical ABRITSA formula consisting of (1) one component with eight elements (Infectious Agents), (2) one component with three elements (Hazard Zone by risk), (3) two components with two elements, and (4) four components with one element. The total complexity of the graphic was expressed as 20 elements for 11 components (Table 5.5).

The contextual information was transcribed into *a cartographic message* and implanted in the following **graphical structure**: the invariant – a geographic order, which takes two orthogonal components (X and Y), and the nine retinal components (Z) represented with the retinal variables, such as color, texture, size, shape, and symbol.

Table 5.5: The Designed Graphical Image Complexity Formula

VISUAL VARIABLES	COMPONENTS	EXAMPLES
Map	1	Wards (50)
Color	4	Red, Gray, Yellow, and Green
Size	3	Large, Medium, Zero
Texture	1	Lines
Symbols/shape	5	Dot, Circle, Text, Cross Line, Brick

The components that are presented with continuous data require a different graphical structure; they can be presented with diagram. Figure 5.8 presents a demonstrational unit for the visualized mapped data.



5.10. Discussion

There is a critical need to develop new representations of healthcare data to increase healthcare practitioners' SA and to reduce cognitive burden. The efficient graphics can furnish large amount of the electronic health record data into a single image. The graphics may play significant role when the monitoring needs rapidly increase during emergencies, for instance during infectious outbreaks or epidemics, or other situations characterized with a high rate of environmental changes.

The proposed ABRITSA cartographic message may enable users to identify high-risk for infection transmission locations, regarded as high priority for infection control services; to identify patients who are at high risk for exposure to ABR pathogens, regarded as high priority for infection prevention services; to recognize the areas where the risk of infection transmission is significant, regarded as hazardous environments, and, ultimately, to assess the infection prevention needs in the context of these risks for work planning, patient arrangements, resources allocation, or targeted monitoring of compliance. A combination of the patient's infection state, contact frequency, and receipt of the infection prevention intention provides

a strong signal for actions, e.g., reinforcing the compliance with the existing policies or developing new tactics for specific situations.

Mapped data provides instantaneous answers, making the groups and potential explanations appear with exceptions. The contribution of this research is the development of an innovative ABRITSA-oriented GUI, a new form of medical knowledge representation where spatially linked clinical data can be used for spatial decision-making in hospitals.

5.11. Summary

Chapter 5 represented the innovative study in the field of healthcare data representation. In Chapter 5, the investigator applied the graphical design method and transcribed the ABRITSA model concepts, aided with the data from the local EHR, into the graphical image. The proposed cartographic message yields the situational awareness-oriented GUI for infection control. The map of a 50-bed unit has enabled the investigator to reduce the conceptual complexity of the infection information into the 11-component graphical structure consisting of 20 elements. The image that represents 11 components serves as an “inventory” message. The lessons learned by the investigator included:

Key Points

1. Visual information processing appears a valuable method for representing a complex clinical informational set in an understandable manner.
 - The main elements of the visual information processing include: (a) the elimination of certain correspondences, (b) the visual ordering and classing, and (c) the superimposition of images.
 - The elimination of some information reduces the image conceptual complexity;
 - Ordering of some elements into new concepts and superimposing of several images make the image memorable;
2. The effectiveness of the graphically processed information depends on the choice of visual variables that facilitate visual selective and associative perceptions.
3. The effective visual information representation can reduce information conceptual complexity and increase the speed of discovering the groups at infection transmission risk. By mapping the MIS

concept, the investigator managed to discover the areas of high risk for infection transmission and patients at risk of exposure to ABROs. By drawing numerous sketches, the investigator proposed a novel graphical solution.

Making the proposed graphic available to the entire healthcare team, including front-line staff, middle managers, and hospital administration, would effectively support a shared mental picture and enhance sense making about ABR hazardous locations and changing infection transmission risks.

This research needs to represent “super-spreaders”, the individuals at highest risk of exposure to ABRO, for supporting Level 2 SA. This information will be obtained during the development of a simulation scenario for addressing Aim # 3. Chapter 6 will address Aim # 3: To evaluate the impact of the developed GUI design on the users’ SA by comparing with the SA permitted by the current practice. In Chapter 6, the investigator provides a literature review on the methods used for system design evaluation; describes the objective and methods of the quantitative study; and discusses the study results, strengths, and limitations.

CHAPTER 6: A QUASI-EXPERIMENTAL, PRE-POST EVALUATION OF THE NOVEL GRAPHICAL INTERFACE DESIGN EFFECTS ON USERS' INFECTION PREVENTION SITUATION AWARENESS

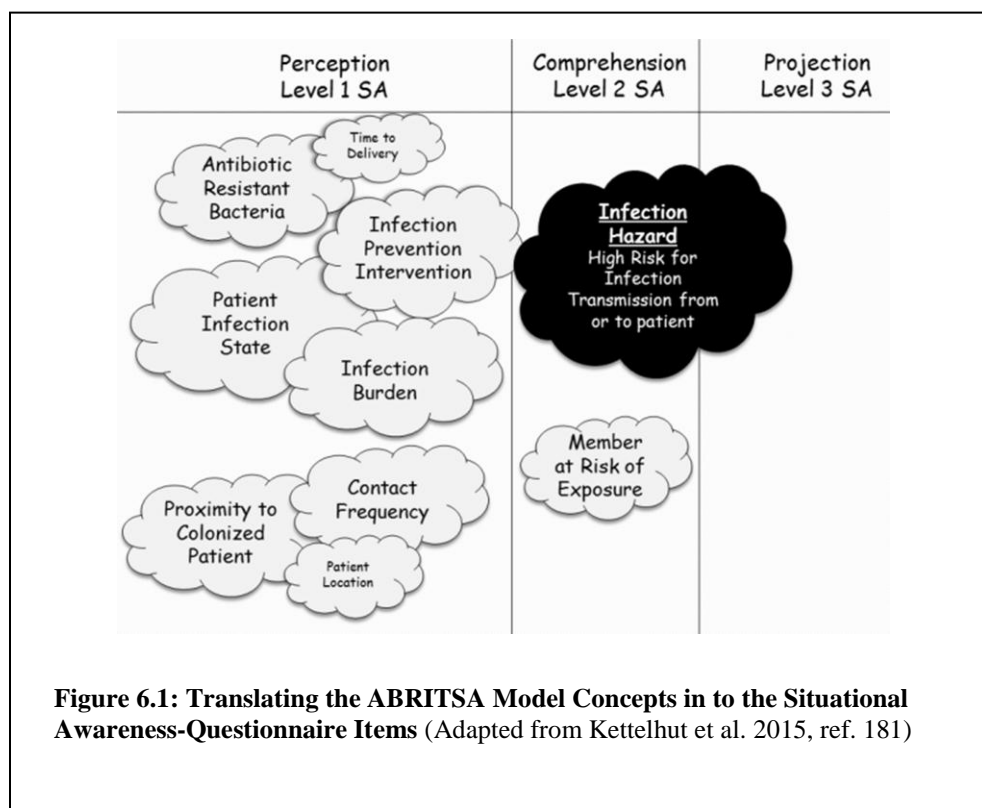
6.1. Introduction

Chapter 6 represents the final study of the Ph.D. work. The overall goal of this Ph.D. work was to apply a situational awareness (SA) approach for designing a GUI to impact healthcare practitioners' SA regarding high-risk situations for ABR infection transmission in hospitals. In the previous chapters, the investigator has established the operational definition for the antibiotic resistant infection transmission situational awareness (ABRITSA); formalized the conceptual ABRITSA model; examined the epidemiologic environment of the study medical-surgical unit with the use of surrogate, proxy, and process measurements, and the EHR data; and transcribed the ABRITSA informational content into the graphical features. The ABR infection transmission situational awareness was defined as a perception of the infection transmission risks (Level 1 SA) and a comprehension of these risks (Level 2 SA) in the context of patient and healthcare practitioner's safety. The goal of a graphical interface design was to enable healthcare practitioners to gain a high level of understanding about the high-risk ABRIT situations (Level 2 SA) quickly.

Chapter 6 addressed Aim #3: To evaluate the impact of the developed GUI design on the users' situational awareness by comparing with the situational awareness permitted by the current practice. Healthcare is rapidly adapting the SA-oriented approach for system and interface design to address various clinical needs. Early evaluation of new interface features is an important step in the design process for better understanding, whether it aids or undermines SA. A key for success in producing a safe and effective IT product for clinical practice is a continuous iterative testing from the conception to the final product. The early evaluation allows the researcher to address the needs of clinical practice, medical specialty, unique operational workflows, and innovations. The overarching goal of the developed graphic for the

ABRITSA user interface is to increase the accessibility and memorability of the infection transmission information in order to increase the user's SA in the fastest and easiest way.

The objective of this final study was to conduct a pilot evaluation to obtain preliminary evidence on the degree to which a GUI for tactical biosurveillance impacts operators' self-reported SA by measuring operators' SA via a cross-sectional survey. Specifically, the study measured how a person evaluates his or her perception of the data associated with infection transmission risks and prevention (Level 1 SA) and understanding of the significance of the risks in a simulated situation (Level 2 SA). Figure 6.1 shows a distribution of the ABRITSA concepts among Level 1 SA and Level 2 SA. The Level 1 SA concepts are represented with the data elements, while the Level 2 SA concepts represent "insight".



6.2. Background

Situational awareness (SA) is a fundamental concept used to maintain operational safety in high reliability organizations. Many poor decisions have been attributed to poor SA; therefore, more SA seems beneficial for overall performance.[61] According to Endsley, the term SA emerged as a psychological concept comparable to various terms, such as intelligence, vigilance, attention, fatigue, stress, compatibility, and workload.[51] More generally, SA is defined as the knowledge state that can be achieved. It encompasses knowledge of current data elements (Level 1 SA), inferences drawn from these data (Level 2 SA), and predictions that can be made using these inferences (Level 3 SA). According to Endsley, the amount of SA differs in experts vs. novice where novice can be neither the experienced nor the expert. The system designers need to recognize that there may be ideal, achievable, and actual SA. If actual SA is poor, for example due to inattention to the data elements or inability to comprehend the information, then there is a weak basis for making interpretations.[68] Ideal SA is the amount of knowledge that exists in the universe during a certain period necessary for achieving specific goals successfully. The achievable SA, according to Endsley, reflects the success of developed displays that ensure the attainment of the operator's goals. The difference between achievable, ideal, and actual SA helps evaluate how different individuals achieve the desirable level of SA as well as the extent of training needed.

SA Measurement Methods and Measurement Tools

Measurement of SA is often limited to perception, comprehension, and projection processes. The rigorous way to measure SA is to restrict the investigation to Level 1 SA, the features of the environment that a person can recall. However, Levels 2 and 3 SA are more informative and important for decision-making. The majority of SA evaluation metrics and tools have been developed for aviation, airspace, and military fields.[66, 196] A few tools for measuring SA in healthcare are known as part of crew resource management.[197-199]

The SA metrics include subjective and objective measures of operator's cognitive states and performance. All SA measurement methods can be broken down into four categories:

1. Direct system performance measures;
2. Direct objective experimental measures;

3. Verbal protocols; and
4. Subjective measures.

Direct objective experimental methods: Queries or probes represent the most common direct objective SA measurement method. Probes are best to use when the pace of the task is slow or has many periods of inactivity. Probes are introduced during ongoing tasks and used during a simulation that employs a system: the operators' work is interrupted at random times (the freeze technique), and the assessment of their SA takes place. The operators have to answer questions about the state of the task or the environment before resuming the task. The assessment includes questions about perception of data, comprehension of meaning, and projection of the near future. Endsley formalized this method as Situational Awareness Global Assessment Technique (SAGAT). The SAGAT is a tool used to assess each level of operator's SA directly. As a result, SAGAT provides the objective assessment of operator's SA. SAGAT does not require subjects to make judgments about situation knowledge on the basis of incomplete information. Then, the collected detailed information on subject's SA is compared with the reality. By collecting samples of the SA data in this manner, situation perceptions can be collected immediately. The most critical component of this method is developing the queries for specific experiments and aspects of the situation.

SAGAT can be used for the comparison of different displays. for the evaluation of their effects on operators' SA. SAGAT is extensively used in studying air traffic controller's SA. Typically, the studies measure SA related to location or deviation from desired course in the environment with a high rate of changes. The main disadvantage of this method is its intrusiveness due to the freeze technique.

Subjective measurement methods: SA self-rating technique (SART) is the most frequently reported technique in many studies. SART measures can be obtained with several methods, including operators self-reporting, expert judgments, peer ratings, or instructor ratings. The main advantage of this technique is the ease of its use and low cost. The disadvantage of SART is its subjective nature due to the possible influence of perceived performance. The SART technique was developed by Taylor (1990) to measure self-perceived SA in aviation.[200] Taylor's SART instrument allows operators to rate a system design via seven-degree scales of perception experienced for the following constructs: instability of situation, complexity of situation, variability of situation, arousal, concentration of attention, division of

attention, spare mental capacity, information quantity, and familiarity with situation. Measurements of speed and accuracy of responses allow an overall estimate of the subject's SA. SART is useful in the early phase of the system development for low fidelity evaluations.

Verbal protocol is the most useful technique for an early evaluation of the system design. The subject is asked to explain the information they relied on during or immediately after an exercise using a "think aloud" technique. Although this technique is disruptive, it allows solidification of SA concepts for measuring them more systematically. This approach represents a collaborative effort with domain practitioners to accurately capture knowledge of the domain and of the complexity of operations.

Direct system performance methods is recommended for specialties when detection and understanding of the system anomaly is central to successful performance. Correspondingly, the purpose of such displays is to support this understanding. This method is used infrequently because it requires extensive up-front planning for designing the scenarios. The scenarios are manipulated by introducing anomalous data, erroneous instrument reading, or disruptions intended to disorient the operation. Measurement of the operators' time to detect anomaly, take action, and recover from the disorientation is used for evaluation of the system design. For example, Hahn and Hansman (1992) evaluated the utility of graphical, aural, and textual communication links by measuring the time taken by pilots to recognize faulty air traffic control directives, which were introduced as part of the experiment.[201]

Alternative Approaches: There are some situations and tasks for which the cognitive decision-making approach is not well suited. Endsley points out that some conditions include tasks that are "highly repetitive, lack clear feedback, or do not result in dramatic or memorable incidents". For these situations, researchers employ an alternative method called Process Tracing (PT) with the use of simulated incidents. Researchers introduce a few hypothetical probes, or as a simulation scenario, to collect detailed data. PT can be highly informative about SA as it relates to judgment and decision-making in simulated tasks. Researchers can study both experts and novices in the same tasks to compare their SA and then examine the difference in SA. Although this method offers a wide variety of data gathering opportunities, it has some weaknesses. The simulation is limited to the variables that the researcher already knows, or are unrealistic.

6.3. A Theoretical Framework for Developing the ABRITSA Assessment Instrument

Literature lacks information about how individuals communicate situational awareness about infection transmission risks in operational settings. Toner critiques that much emphasis is placed on the systems to detect outbreaks rather than on the systems to manage outbreaks.[69] He points out that there are some fundamental issues related to the knowledge of what information really makes a difference in healthcare. In order to assess operators' ABRITSA, it is critical to design a questionnaire with explicit questions about infectious risks. Thus, the investigator has adopted the framework developed for health and ecological risk-assessment (RA).[202-204]

In general, RA is a systematic process for describing and quantifying the risks associated with hazardous substances, processes, actions, or events. The RA methods consider risk as a two-dimensional concept involving (1) the possibility of an adverse outcome and (2) uncertainty over the occurrence, timing, or magnitude of that adverse outcome. Risk is defined “as a characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown, and at least one of the possibilities is undesired”. [205] In application to healthcare, RA is defined as “a systematic process for generating a probability distribution or similar quantification that describes uncertainty about the magnitude, timing, or nature of possible health or environmental consequences associated with possible exposure to specific substances, processes, actions, or events”. [205] RAs deal with more than a single individual while a description of individual risk can take various forms. The risk managers are supposed to answer key questions in mapping out a strategy for dealing with individual risk. They have to estimate the probability that an individual may suffer an adverse effect given a specific set of exposure circumstances.

RA methodology could provide a framework for a systematic assessment of both the infectious risks as part of care planning process for each patient and the occupational exposure to ABRO for each HCP. Such information can be invaluable when considering various actions for effective and efficient mitigation of infectious transmission risks in hospital settings for individual patients and HCPs. For example, in the United Kingdom hospitals, it is recommended to document all precautions for infection prevention within the patient's individual plan of care, regularly assess and reassess the risks, and make

changes as necessary as the patient's condition alters.[74] A general RA process includes three distinct activities, including characterization of (1) risk (hazard) source release processes, (2) exposure processes, and (3) consequence processes.

Hazard identification (HI) and release assessment quantify the potential of a hazard source to introduce risk agents into an environment, and include a description of the types, amounts, timing, and probabilities of the release of toxic substances, radiation, kinetic energy, **microorganisms**, and other risk agents. Exposure assessment (EA) describes and quantifies the conditions and characteristics of environment as well as human exposure to these risk sources and their product. EA describes the intensity, frequency, and duration of exposure, the routes of exposure (through the skin, the blood, air, etc.), the characteristics of **people at risk of exposure**, and other important conditions. EA is the process of measuring or estimating the *magnitude, frequency, and duration* of human exposure to an agent in the environment. This step is critical for understanding a dose of exposure and answering the questions such as: *“How much of the agent are individuals exposed to during a specific period?”* *“How many people are exposed?”* EA includes some discussions of the size, nature, and types of human population exposed to the agent, as well as discussions about uncertainties.[202] For any specific site or agent, there is a range of exposure actually experienced by individuals. Some individuals may have a high degree of contact for an extended period. Other individuals may have a low degree of contact for a shorter period. EA can be used to determine whether exposure occurs and to monitor status and trends. Exposure status is the snapshot of exposure at a given time, usually the exposure profile of a population or population segment. Medical epidemiology utilizes a term called “effective dose”. For example, the recent Ebola outbreak showed that a negligible amount of Ebola virus is effective to cause the disease in human.

Consequences assessment (CA) describes and quantifies the relationship between the specified exposures to a hazard and the health effects. In practice, it is difficult to establish an accurate health effect risk for a population or dose-response relationships. This challenge relates to uncertainties in using animal data for human dose-response relationships, projecting incidence data from one group to a dissimilar group, non-linearities in the dose-response curve, and other. Therefore, these estimates are not meant to be accurate predictors of disease. The estimate's value connects to the framing of hypothetical risk in an understandable way. Finally, risk characterization is a conclusion of the risk assessment process for both

ecological and health risks. Risk characterization serves as a primary vehicle for communicating health RA findings.

For developing an effective interface for communicating risk of ABRs in hospitals, the information should present (1) who is a source of risk, (2) who is at risk, (3) how they might be affected, (4) what the severity and reversibility of adverse effects might be, (5) how confident the risk assessors are in their predictions and other qualitative information. The use of surrogate measures for infectious risk assessment has been communicated in Chapter 3 and Chapter 4. Theoretically, the value of the ABRITSA interface may emerge when the designer manages to frame the ABR risks in an understandable way that provides instantaneous answers, making the groups and potential explanations appear. Based on the RA framework and the ABRITSA model, the investigator has developed a **pilot questionnaire** for communicating infection transmission risks (Appendix A 1 and 2).

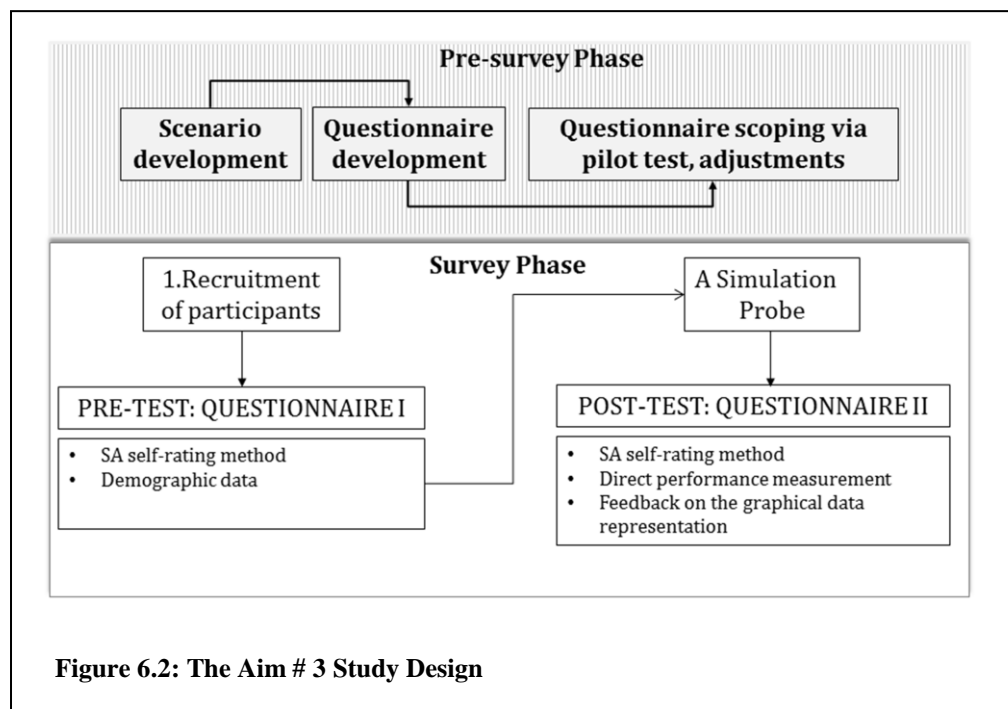
Instrumentation: The investigator created a questionnaire to measure how individuals perceive their SA regarding spatial disease distribution in an enclosed environment and spatially linked exposures, behaviors, and interventions for the current practice vs. the proposed GUI. This questionnaire served as a self-rating instrument including a 5-point Likert scale where 1=lowest score and 5=highest score. The investigator utilized a *risk assessment framework* for building the questions to measure Levels 1 and 2 SA in the infection transmission domain. The content validity and construct validity of the instruments are not established yet because this is a novel instrument. However, the instrument includes the items on the risk factors based on the body of knowledge available today about antibiotic-resistant infection transmission for direct contact, indirect contact, and fecal-oral transmission modes.

The instrument represents a short pilot version questionnaire, which deems sufficient for the low fidelity testing. Reliability of this instrument is not been established yet.. The major content sections in the instrument include: (1) a notation about anonymity of responses; (2) the demographics and knowledge items; and (3) the closing instructions. The instrument includes the seven SA-items in the pre-test (Q1-Q7) and post-test (q1-q7) to measure Level 1 SA and Level 2 SA; one item in the pre (Q8) and post (q8) test to measure the “attitude about a risk of exposure”, one multiple-choice item in the post-test (q6 a) to measure subject’s direct performance, and post-test items (q 9-q12) to measure subject’s perception of the

ABRITSA GUI and the training material usability. Pre-post measurements of SA of each individual was taken on a 5-point scale, where 1=lowest SA and 5=highest SA. The unit-based vs. non-unit participants were surveyed at their main locations in the hospital to increase participation rate.

6.4. Study Design and Methods

The Aim # 3 study employed a quasi-experimental survey with pre-post design based on the inductive approach. The pre-survey phase included (1) development of the instrument for survey and (2) validation of the questions with a focus group. The survey phase included (1) enrollment of participants, (2) administration of the pre-questionnaire followed with the introduction of the GUI, administration of the post- questionnaire, and verbal feedback (3) analysis of the survey results and (4) development of the new specifications for the GUI (Figure 6.2).



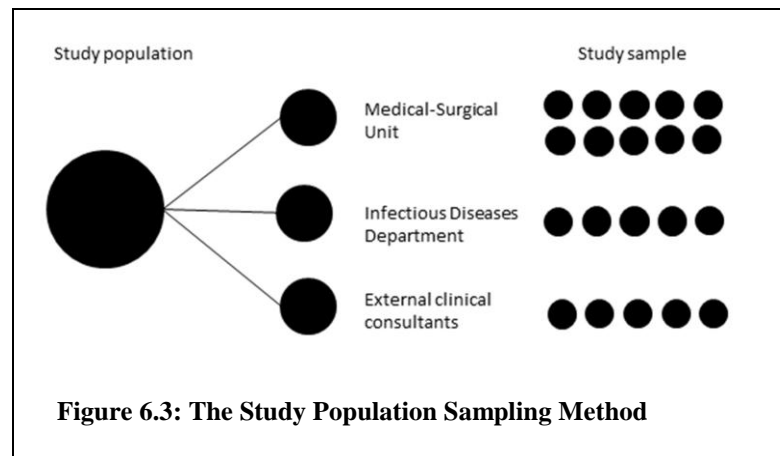
The survey was administered via the questionnaire in a group format. The investigator has employed a simulated scenario by using a one cross-sectional snapshot of the EHR data displayed with the

developed ABRITSA graphical interface. The survey has collected the self-rating data from the subjects at one point in time due to the study's exploratory nature. This activity was conducted from January 2015 to April 2015.

Study Setting: The study setting chosen is a 50-bed medical-surgical unit at a Midwest teaching hospital. The unit includes the North and South parts. The North part accommodates 10 wards used mostly for severely ill cancer and elderly patients, totaling 3,904.44 square feet, with 205.5 square feet per ward, on average. The South part accommodates 27 wards utilized mostly for general surgery and transplant patients, totaling 5,168.16 square feet, with 192 square feet per ward, on average.

Participants: Participants included care technicians and nurses involved in the care in this unit, hospital infection preventionists, and on-demand clinical consultants. The subject enrollment in the sample was performed in three ways: (1) a solicitation sponsored by the unit management group; (2) a solicitation sponsored by the Executive Director of Infectious Disease and Epidemiology Department; and (3) through a verbal solicitation by the investigator.

The sampling design for this population was multistage (Figure 6.3). The investigator sampled the groups and then obtained a sample within the cluster. This sampling addressed the need to study individuals varied in their task characteristics and locations, including the delivery (operational) and decision-making representatives. The individuals were selected in a conventional manner due to the organizational constraints (e.g., the hospital employs a total of six infection preventionists). The selected population was stratified into two groups: "unit-based staff" vs. "non-unit-based staff" with regard to specific location. The size of each stratum was approximately equal. The "non-unit" group included clinical consultants, who visit the unit on demand, and infection preventionists. The "unit" group included the unit staff.



In addition, in order to control the type of information used, the sample had to be drawn from the population that uses the same EHR system and the methods of sharing of hospital infection surveillance information. The hospital EHR has the functionalities to create awareness in the hospital staff about patients' ABRO carriage status (e.g., flagging method).

The needed sample size was at least ten subjects to allow the application of non-parametric statistical techniques. The informed consent was administered among the subjects at the beginning of their participation. The investigator obtained the approval from the University of Nebraska Medical Center IRB (IRB# 171-15-EX).

6.5. Developing a Simulated Event

The investigator developed a simulated event in order to introduce the GUI. The simulated event included displaying the medical-surgical unit information about the infectious risks with the two views for a hypothetical day. For this, the investigator has developed the **two interface views**: (1) the Unit Transmission Hotspots Map 1 (Figure 6.4) and (2) the Unit Analytical Map 2 (Figure 6.5).

Map 1 represents a cross-sectional view of the medical-surgical unit population epidemiology for one day. Map 2 represents a longitudinal view of daily epidemiological statuses.

To make the simulation close to a real world situation, the investigator utilized the EHR empirical data related to the daily spatial distribution of the patients with ABR infections, antibiotic usage,

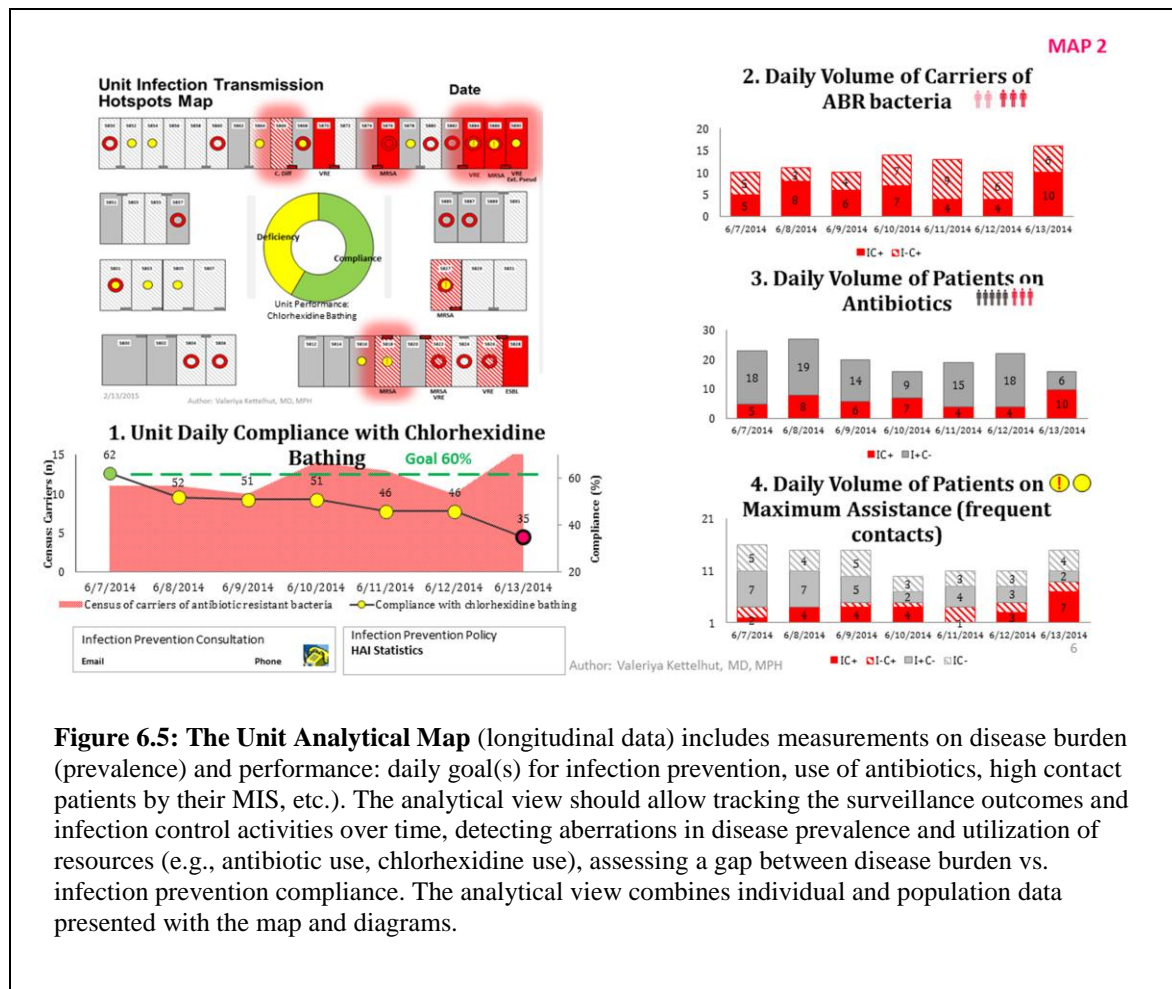


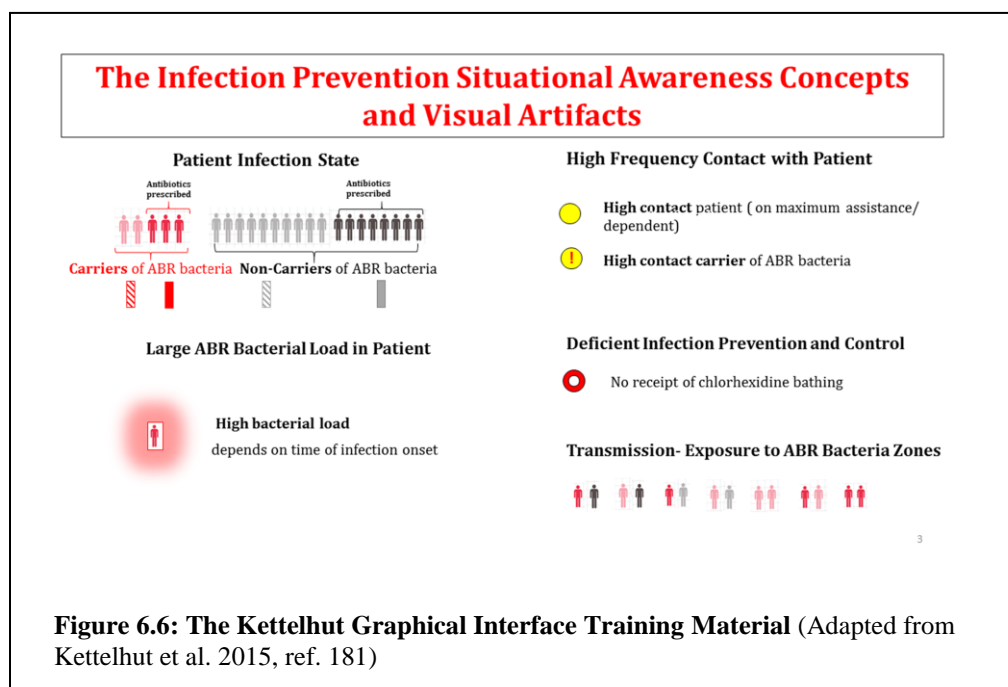
Figure 6.5: The Unit Analytical Map (longitudinal data) includes measurements on disease burden (prevalence) and performance: daily goal(s) for infection prevention, use of antibiotics, high contact patients by their MIS, etc.). The analytical view should allow tracking the surveillance outcomes and infection control activities over time, detecting aberrations in disease prevalence and utilization of resources (e.g., antibiotic use, chlorhexidine use), assessing a gap between disease burden vs. infection prevention compliance. The analytical view combines individual and population data presented with the map and diagrams.

6.6. A Pilot Validation of the Questionnaire, Training Materials, and the Graphical Interface

Prior to the survey phase, the investigator conducted a pilot validation of the survey in order to establish face validity of the instrument and to improve the content of both, the questionnaire and the training material. For this, the investigator invited the unit manager and the quality nurse to form a small focus group. During three meetings, the group developed a list of recommendations for the questionnaire and for the survey implementation. The first recommendation advised the research to administer the questionnaire among the unit-based group members early morning to increase participation rate. The second recommendation was to reduce the number of the questionnaire items in order to allow the participants take approximately 30 minutes out of their work to complete the study. The third

recommendation was to re-format several questions and make them more relevant for the unit staff vs. non-unit staff members. The group revised each question to make sure it was clear, concise and without bias. The language level used in the instrument for the front-line staff was targeted towards those at the lowest educational level. In addition, the investigator checked the questionnaire on the presence of double-barreled questions and the questions with negative items and/or causality. The questionnaire included open-ended questions. The final ABRITSA questionnaire included five questions for self-reported Level 1 SA, two questions for self-reported Level 2 SA, and one question for direct user's performance. The rest of the questions were designed to understand usability of the GUI and the training materials. After the validation, the investigator formatted the questionnaire to achieve an appealing aesthetical and logical order, starting with easier questions and moving toward more challenging questions.

The focus group accepted the training materials as adequate, and provided additional feedback for the GUI design. Specifically, after a series of iterations, the group decided to modify the “Hazard Zone: Transmission Risk” artifact by reducing the three-component image to a one-component image. The one-component visual artifact reduced the conceptual and visual variability. It also simplified the discrimination of “significant bacterial load” for the “recent” ABR infections from the “old” infections and retain the meaningful information from the practical perspective concerning infection prevention (Figure 6.6).



6.7. The Survey Process

The investigator held the meetings with the unit-based and non-unit participants separately. At each group meeting, the investigator briefly explained the purpose of the study and verbally communicated the informed consent lasting. This task took on average 4 minutes (Figure 6.7). After the introduction, the participants took the pre-test by proving their answer to the first part of the questionnaire. On average, this task took approximately 7-8 minutes. The pre-test data were used to measure the subjects' baseline SA attributed to their current practice of the EHR use.

Then, the investigator provided a short training to the group by introducing the GUI and explaining the meaning of the GUI visual artifacts and concepts with the use of the training material (Figure 6.6). Subsequently, the participants performed a simulated review of the Map 1 and Map 2, which displayed the unit patients' risks. All participants then took the post-test questionnaire at their pace, using Map 1 displaying the snapshot of the unit epidemiological data for one day. This task took approximately 10 minutes. The post-test data were collected for measuring the GUI-based SA.

At the end, the investigator collected the verbal feedback to maximize the knowledge acquisition from the participants regarding the usability of the GUI. The investigator took notes of the verbal communication and summarized the commentaries into a qualitative feedback. All recorded responses were transcribed, coded, and analyzed.

Research Study: Survey

- **Purpose:** to explore how a new interface impacts HCW's situational awareness about risks of infection transmission and exposure to ABR infections
 - Situation awareness: knowing what is going on around me at any point in time
- **Anticipated benefits:** innovative tactical and strategic decision-making for better prevention and control of ABR infection in real time

- **Process:**
 1. Survey Part 1 2 min
 2. Demonstration 7-8 min
 3. Survey Part 2 3-5 min
 4. Feedback
- Anonymous responses
- Minimum risk for participants
- The right to withdraw from the research at any time

Contact with PI:
vkettelhut@nebraskamed.com

Figure 6.7: The Study Consent Information

6.8. Statistical Analysis

All participants were categorized as being either unit or non-unit staff and assessed pre-intervention and post-intervention. Due to the same participants being measured twice, the Wilcoxon sign test was used to compare the median of two dependent samples. The test is appropriate for interval or ratio data that are not normal, or for ranked/ordinal data. The Wilcoxon test creates a pooled ranking of all observed differences between the two dependent measurements. It uses the standard normal distributed z-value to test significance. The statistical program SPSS v.21 was used to sort the observations according to the test variable and assign ranks to each observation, correcting for tied observations. The sample size of 19 seems appropriate for this statistical method.

Main Hypothesis

Ha: *The novel interface design will increase healthcare practitioner's situation awareness. This effect will be greatest in those without access to all patient records, without prior knowledge about patient surveillance status, and less experienced.*

- $H_0: \mu_{EHR} = \mu_{Interface}$ or $\mu_{EHR} - \mu_{Interface} = 0$ $H_0: \mu_D = 0$
- $H_a: \mu_{EHR} < \mu_{Interface}$ or $\mu_{Interface} - \mu_{EHR} > 0$ $H_0: \mu_D > 0$
- Significance level: alpha-level ≤ 0.005
- Region for rejection: Reject the null if p-value ≤ 0.005

The dependent variables included Level 1 SA, Level 2 SA, total SA, and usability of the new interface design (Table 6.1). The independent variables included user's experience (years of healthcare experience), role (nursing aid, nurse, and physician), and access to patients' records in the EHR (Table 6.1). The pre- and post-SA measures and usability measures of each individual were taken on a 5-point Likert scale.

The SA measurements were defined for:

1. a measurement of Level 1 SA as a sum of the self-perceived rating scores in the answers about patients who are carriers of ABR bacteria (Q1/q1), locations of these patients in the unit (Q2/q2), type of bacteria identified in these patients (Q3/q3), patients who receive antibiotics (Q4/q4), and patients who did not have chlorhexidine bathing in the previous 24 hours (Q5/q5);

2. a measurement of Level 2 SA as a sum of the self-perceived rating scores in the answers about circumstances when the risk of antibiotic-resistant infection transmission increases (Q6/q6) and individual level of exposure to ABR infections (Q7/q7); and
3. a measurement of Total SA as a sum of Level 1 SA and Level 2 SA.

Table 6.1. Aim # 3 Variables, Research Questions, and Items of Questionnaire

VARIABLE NAME	RESEARCH QUESTION	ITEM OF SURVEY
Independent Variable # 1 Access to all patients' records	How many individuals can access the records of the all patients bedded on a specific unit?	Part I - a question about the authorization, validation with the unit management
Independent Variable # 2 Years of experience in healthcare	What number of years has an individual worked in healthcare?	Part I Q 10
Dependent Variable # 1 (Total Situational Awareness)	How has the team perceived its overall awareness about the model-based infection transmission risk factors? Is there any difference in scores between sub-groups?	Part I and Part II: Q/q 1-5
Dependent Variable # 2 (Level I Situational Awareness)	How has the team perceived its overall awareness, Level 1 Situational Awareness, and Level 2 Situational Awareness about the model-based infection transmission risk factors? Is there any difference in scores between sub-groups?	Part I and Part II: Q/q 1-5
Dependent Variable # 3 (Level 2 Situational Awareness)	How have the participants perceived their awareness about the situations at high- risk for infection transmission? Is there any difference in scores between sub-groups? How have the participants perceived their awareness about personal occupational exposure to these risks?	Part I and Part II: Q/q 6-7
Dependent Variable # 4 Exposure Awareness (Level 2 Situational Awareness)	How have the participants perceived the importance of knowing personal occupational exposure to these risks?	Part I and Part II: Q/q 8
Dependent Variable # 5 Usability of Training	How have the participants perceived the usability of the training material?	Part II: items q12
Dependent Variable # 6 Usability of the Interface	How have the participants perceived the usability of the interface design?	Part II: items q 9-11

6.9. Results

Nineteen healthcare practitioners (n=19) participated in the study. The study sample included 10 (53%) medical-surgical unit staff members and 9 (47%) non-unit-based consultants. There were 16 (84%) nurses (RNs), one (5%) resident (MD), and one (5%) nursing assistant (NA). The nursing group consisted of nine unit-based RNs, three non-unit palliative care RNs, and five non-unit infection preventionist RNs. Seven of 19 (37%) HCPs had less than five years health care experience and were the unit-based RNs. All participants had access to the EHR: the infection preventionist RNs have authority to access all hospitalized patients' records, consulting HCPs and unit bed-side RNs can access only their patients' records, and the unit managers can access any patient record if a patient is bedded on their unit.

Construct validity of the survey was assessed using Cronbach's alpha (Table 6.2). To assess the level of "infection situation awareness", the following survey items were used Q1, Q2, Q3, Q4, Q5, Q6, and Q7. The Cronbach's alpha for the seven items was 0.891 and the corrected item-total correlation for each item was > 0.30.

Table 6.2: The Questionnaire Construct Validity Measurements (Cronbach's Alpha)

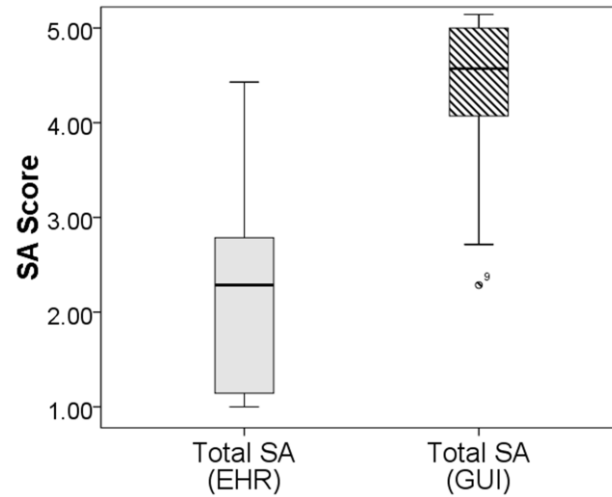
<i>Items</i>	<i>Corrected Item-Total Correlation a cut-off for weak correlation =0.30</i>	<i>Cronbach's Alpha if Item Deleted</i>	<i>Cronbach's Alpha</i>
<i>Q1</i>	0.763	0.866	0.891
<i>Q2</i>	0.730	0.871	
<i>Q3</i>	0.742	0.869	
<i>Q4</i>	0.484	0.895	
<i>Q5</i>	0.687	0.875	
<i>Q6</i>	0.560	0.889	
<i>Q7</i>	0.872	0.849	

Team SA Measurements

The investigator took SA measures of 19 healthcare practitioners (HCPs) before and after a brief training. The median overall-team total SA_{EHR} was lower than the median total SA_{GUI} (2.29 vs. 4.57) (Table 6.3). The Wilcoxon signed ranks test showed a significant increase in the median overall-team total SA_{EHR vs GUI} (p<0.001) (Table 6.3). The team significantly increased the median Level 1 SA_{EHR vs GUI} (1.8 vs. 4.6, p<0.001) and Level 2 SA_{EHR vs GUI} (2.0 vs.4.5, p<0.001) (Diagrams 6.1, 6.2, and 6.3).

Table 6.3: Median Overall-Team Situational Awareness Score (EHR vs. GUI)

<i>Overall Team Situational Awareness with EHR vs. GUI</i>			
<i>Item (Median)</i>	<i>EHR (Pre-Test)</i>	<i>GUI (Post-Test)</i>	<i>p-value</i>
<i>Q1</i>	3.00	5.00	0.017
<i>Q2</i>	2.00	5.00	0.001
<i>Q3</i>	2.00	5.00	<0.001
<i>Q4</i>	1.00	5.00	<0.001
<i>Q5</i>	1.00	5.00	<0.001
<i>Level 1 SA Score</i>	1.80	4.60	<0.001
<i>Q6</i>	1.00	4.00	<0.001
<i>Q7</i>	2.00	5.00	0.001
<i>Level SA 2 Score</i>	2.00	4.50	<0.001
<i>Total SA Score</i>	2.29	4.57	<0.001

**Diagram 6.1: Median Overall-Team Total Situational Awareness Score, EHR vs. GUI (n=19)**

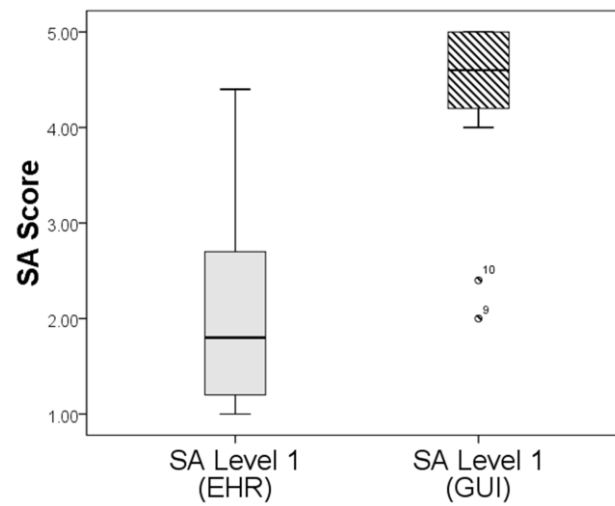


Diagram 6.2: Median Team Level 1 Situational Awareness Score, EHR vs. GUI (n=19)

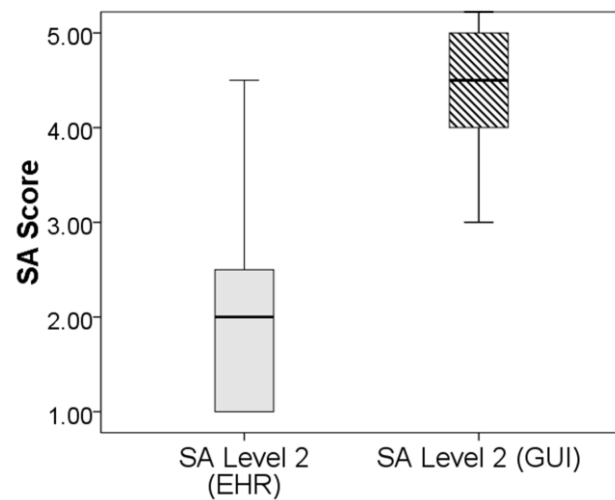


Diagram 6.3: Median Team Level 2 Situational Awareness Score, EHR vs. GUI (n=19)

After stratifying the overall-team SA score by the questionnaire items, the median SA_{EHR} scores showed high variability for Q1, Q2, Q3, and Q7 (range 1,5) (Diagram 6.4) comparing with the median SA_{GUI} scores, most of which were 5.00 (“ceiling effect”) (Diagram 6.5).

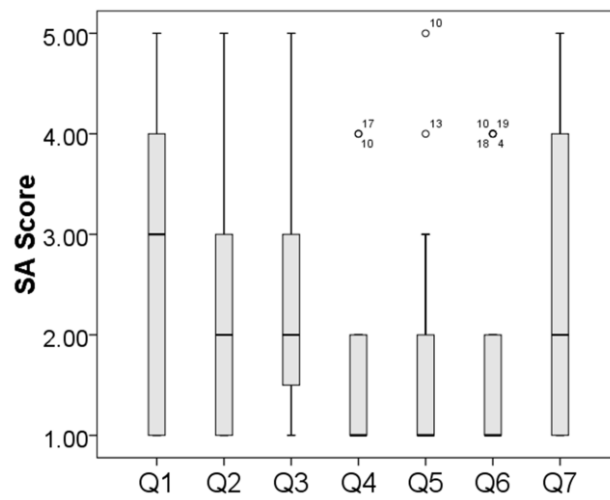


Diagram 6.4: Median Overall-Team Situational Awareness EHR Score by Items (n=19)

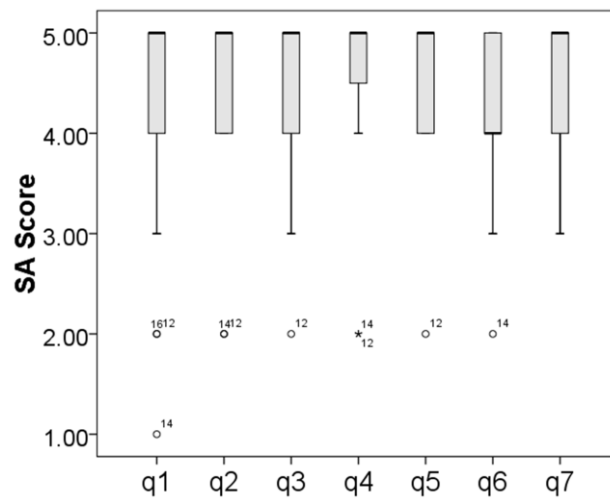


Diagram 6.5: Median Overall-Team Situational Awareness GUI Score by Items (n=19)

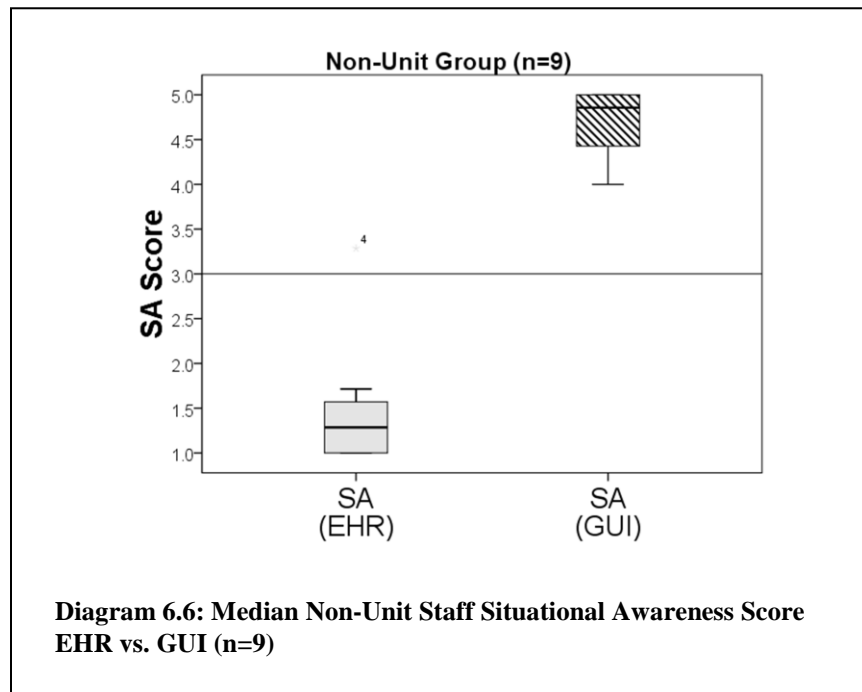
Unit-staff and Non-unit Staff SA Measurements

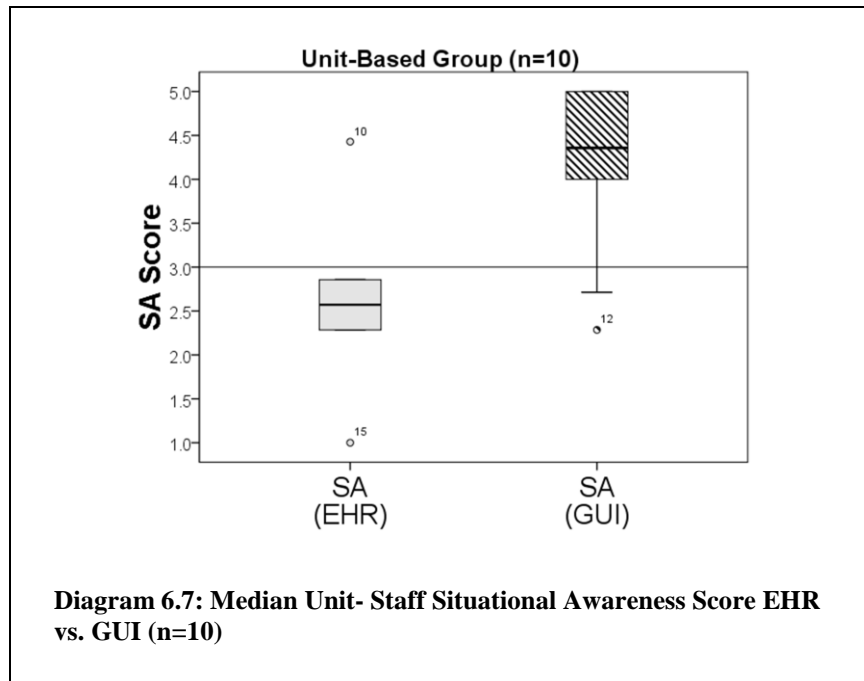
After stratifying the subjects into unit-staff and non-unit staff, the unit staff showed higher baseline median Level 1 SA_{EHR}, Level 2 SA_{EHR}, and total SA_{EHR} scores than the non-unit staff's scores

(2.50, 2.50, 2.50 vs. 1.40, 1.00, and 1.29) (Table 6.4). The non-unit staff had the lowest baseline median Level 2 SA_{EHR} score (1.00).

Table 6.4: Median Situational Awareness Score in Unit Staff and Non-Unit Staff (EHR vs. GUI)

<i>Item (Median Score)</i>	<i>Unit Staff Situational Awareness</i>			<i>Non-Unit Staff Situational Awareness</i>		
	<i>EHR</i>	<i>GUI</i>	<i>p-value</i>	<i>EHR</i>	<i>GUI</i>	<i>p-value</i>
<i>Q1</i>	4.00	4.00	*	1.00	5.00	0.010
<i>Q2</i>	3.00	4.00	0.055*	2.00	5.00	0.007
<i>Q3</i>	3.00	4.50	0.019	2.00	5.00	0.010
<i>Q4</i>	1.00	4.50	0.016	1.00	5.00	0.006
<i>Q5</i>	1.50	5.00	0.07*	1.00	5.00	0.006
<i>Level 1 SA Score</i>	2.50	4.30	0.028	1.40	5.00	0.007
<i>Q6</i>	1.00	4.50	0.011	1.00	4.00	0.010
<i>Q7</i>	4.00	5.00	0.085*	1.00	5.00	0.007
<i>Level 2 SA Score</i>	2.50	4.50	0.012	1.00	5.00	0.010
<i>Total SA Score</i>	2.50	4.36	0.011	1.29	4.86	0.008





Overall, the median Total SA scores significantly increased for each group after using the GUI; although, the unit-staff (n=10) had a smaller increase in the median Total ^{unit}SA_{EHR vs. GUI} (2.57 vs. 4.36, p=0.011) than the non-unit staff (n=9) median Total ^{non-unit}SA_{EHR vs. GUI} (1.29 vs. 4.86, p=0.008) (Table 6.4). The median Level 1 SA and Level 2 SA scores significantly increased in both groups (Table 6.4, Diagram 6.6, and Diagram 6.7). The greatest magnitude of the increase was in the non-unit staff for the ^{non-unit} Level 2 SA_{EHR vs. GUI} score (1 vs.5, p=0.01), while the lowest magnitude of the increase was in the unit staff for the ^{unit} Total SA_{EHR vs. GUI} (2.57 vs.4.36, p=0.01) score. The Wilcoxon signed ranks test showed (1) a significant increase in the median ^{unit}SA_{EHR vs. GUI} scores for Q3, Q4, and Q 6, (2) no difference for Q 1, and (3) insignificant difference for Q2, Q5, and Q 7 in the unit-staff (Table 6.4). The non-unit staff had (1) a significant increase in the median ^{non-unit}SA_{EHR vs. GUI} scores for the all questionnaire items (Table 6.4).

Unit Novice vs. Unit Experienced Staff SA Measurements

The unit- staff was stratified into the novice (n=7) group (1-5 years in healthcare) and the experienced (n=3) group (>5 years in healthcare). The novice group had a higher baseline median Level 1 SA, Level 2 SA, and Total SA than the experienced group (2.40, 2.59, and 2.43, vs. 1.50, 1.00, and 1.36) (Table 6.5). The experienced group tended to have a greater median Level 1 SA, Level 2 SA, and total SA

scores (4.80, 4.80, and 4.79) when using the GUI comparing with the novice group (4.20, 4.50, and 4.28) (Table 6.5.), a pattern similar to the non-unit staff.

Table 6.5: Median Situational Awareness Scores in Unit Novice and Experienced groups (EHR vs. GUI)

<i>Item (Median)</i>	<i>Novice Staff (1-5 years) n=7</i>		<i>Experienced Staff (>5 years) n=3</i>	
	EHR	GUI	EHR	GUI
<i>Q1</i>	4.00	4.00	1.00	4.50
<i>Q2</i>	3.00	4.00	2.00	5.00
<i>Q3</i>	3.00	5.00	2.00	5.00
<i>Q4</i>	1.00	4.00	1.00	5.00
<i>Q5</i>	2.00	4.00	1.00	5.00
<i>Level 1 SA Score</i>	2.40	4.20	1.50	4.80
<i>Q6</i>	1.00	4.00	1.00	5.00
<i>Q7</i>	4.00	5.00	1.00	4.50
<i>Level 2 SA Score</i>	2.50	4.50	1.00	4.80
<i>Total SA Score</i>	2.43	4.28	1.36	4.79

Difference in Individual Participants' SA

Seventeen (89.47%) of 19 respondents positively increased their individual total SA. The EHR vs. GUI total SA difference ranged from 0.50 to 4.50 s (Diagram 6.8). Case 10 showed no difference in SA, while Case 19 showed a negative EHR vs. GUI SA difference (-0.5).

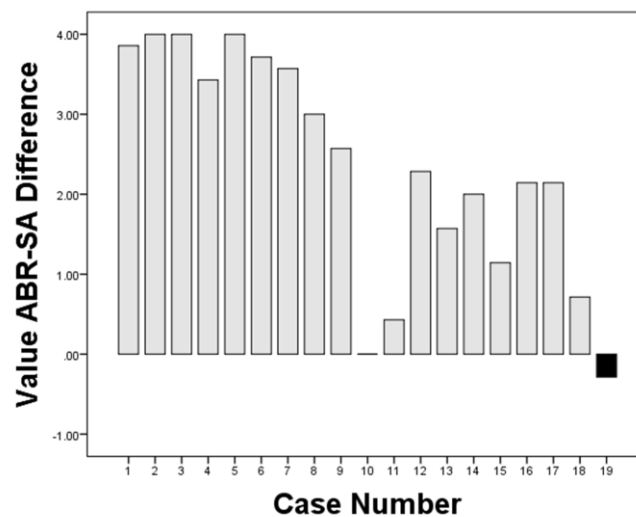


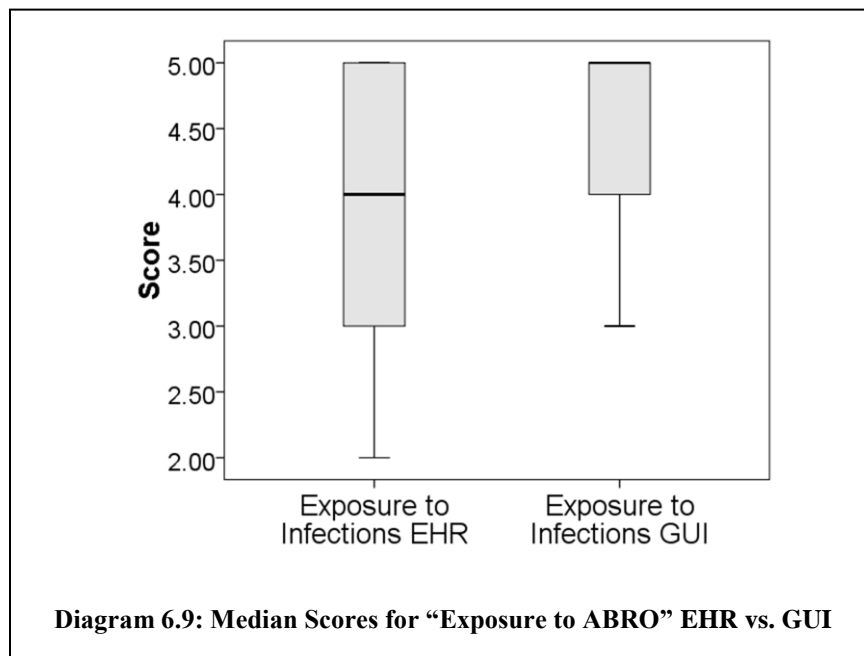
Diagram 6.8: EHR vs. GUI Difference in Individual Total Situational Awareness Score

SA Direct Performance Measurements (q 6a)

The participants were asked to identify at least one location at high-risk for infection transmission using Map 1 (GUI). Seventeen individuals out of 19 (89.47%) provided their responses. All of these responders correctly (100%) identified one location. Two subjects (10.53%) did not respond, yielding the accuracy rate of 89.47%). Overall, each group spent approximately 30 minutes on taking pre-post survey and training.

Risk of Exposure to Infections Score (Occupational Hazard Q8-q8)

The items Q8 (Part I) and q8 (Part II) measure a belief about the importance of knowing a personal occupational exposure to ABROs. The Wilcoxon signed ranks test showed a significant increase in the median overall-team Q8_{EHR vs. GUI} score (4.00 vs. 5.00, $p=0.03$). The baseline median score for Q 8 was high (4.00), ranging from 2.00 to 5.00 (Diagram 6.9). After using the GUI, the median score for q 8 increased to 5.00 ($p=0.03$), ranging from 3.00 to 5.00.



Perception about Usability of the GUI

Fourteen subjects of 19 (70 %) perceived the GUI as a quicker and easier way to be informed about the risks associated with ABR infections than with the EHR-based current practice (q 9, Part II). Eighteen subjects (94.73 %) perceived that the use of visual artifacts (q 10, Part II) and infection prevention deficiencies (q 11, Part II) persuasively alerted them about the presence of infection transmission hazards. Fifteen subjects (78 %) responded that the training material was easy to understand (q 12, Part II). The team median score for q 9 was 5.00 (range 3, 5), q 10 was 5 (range 3, 5), q11 was 4.00 (range 2, 5), and for q12 was 4.00 (range 2, 5).

Qualitative Feedback

After taking the pre-post survey, each group had a verbal discussion about the GUI. The comments were analyzed and transcribed into the four following themes: (1) the GUI's positive effect on clinical practice decision-making, (2) a need for the knowledge about occupational exposure to ABRIIs, (3) the GUI information delivery in a workflow, and (4) the GUI usability (time, cognition, and design) (Table 6.6).

Table 6.6: Qualitative Feedback on the GUI Effects

GROUP	RESPONDER	COMMENTS
Impact on Clinical Practice	Infection prevention staff Unit staff	<ul style="list-style-type: none"> • People do not really understand the need to approach patient care from a “clean-to-dirty” perspective, when “clean” patients need to be taken care prior to approaching “dirty” patients. This interface would help to direct care planning. • Cohorting was one of the recommended practices in the past, when we placed the patients with MRSA in one location and assigned the personnel to provide care only to this group of patients. Currently, we do not cohort, and we do not really know how the unit staff arrange the carriers with different antibiotic-resistant bacteria. This interface shows patients’ arrangements on the unit very well; such information may be helpful for analysis whether the arrangement is safe from the infection transmission perspective. • There is a challenge to make decisions how to better arrange the unit staff. Currently, the managers match patient acuity and staff skills level. The infection prevention module is one piece among many others the managers have to address. • I see how this interface makes the infection prevention and control practice meaningful: patient chlorhexidine bathing clearly appears as a protection for the staff from being exposed to antibiotic-resistant infections. This information is very persuasive for us to do our best.
Occupational Exposure	Consultants	<ul style="list-style-type: none"> • We are often desensitized to our environment; this design makes total sense about the hospital environmental dangers. • I have no idea what is going on a unit when I am called for a consultation. • I need avoid exposure to influenza because of my health issue. I do not know where influenza cases are located. This design would help me protect myself better.
Information Delivery Platform	Consultants Unit Staff	<ul style="list-style-type: none"> • I would like to be notified via my Bluetooth when I am approaching a high-risk zone. I do not have time to check the monitoring screens. • Once we entered a patient room and did not know that the patient required air-drop isolation for tuberculosis at that time. If this interface would inform us at the point of approaching this location, we would use protection and timely isolate this patient.
Usability (Cognition)	Consultants Unit Staff	<ul style="list-style-type: none"> • The visual data informs me in a much better away than the sign on the door. • I feel this interface works better for me than the flag in the EHR. • The colors are associated with danger. • It is very intuitive. • This information is very helpful for me to realize the environmental conditions I am working in. It is very easy to understand what is going on.
Usability (Time)	On Demand Consultant IP	<ul style="list-style-type: none"> • This dashboard informs me in a second about the infectious risks. • This map is a useful quick snapshot of the all patients: we do not see them lamped together as a group.
Usability (Design)	Consultants Random Staff	<ul style="list-style-type: none"> • I prefer a South-North orientation (left-right) rather than the West-East orientation; with the South-North I better know what the rooms are on the map. • Can I see the wound data with this map? • If I administered chlorhexidine bathing, will the program show a decrease in the patient bacterial load?

6.10. Discussion

Measurements of SA are often limited to perception, comprehension, and projection processes. The study employed seven subjective SA performance measures and one direct SA performance measure (error rate) via the pilot pre-post questionnaire. The number of the questionnaire items was limited to a few due to the frontline practitioners' request to take maximum 30 minutes for the survey. Therefore, the choice of the items inclined toward some critical cues. The respondents reported their self-perceived SA levels about (1) patients who are carriers of ABROs, (2) locations of these patients on the unit, (3) type of ABROs, (4) patients who are prescribed with antibiotics, (5) use of the infection prevention intervention, (6) locations at high- risk for ABRIT, and (7) exposure to ABROs assessed with the pilot instrument.

The investigator tested the GUI in 10 unit-based staff and 9 non-unit staff (e.g., infection preventionists) in a 50-bed medical-surgical unit at a Midwest teaching hospital. The non-unit group members had more than five years of experience. The unit-group consisted of seven of 10 (70%) unit-based members with less than five-years in healthcare.

First, the investigator assessed the degree of internal consistency among the set of questionnaire items for measuring situation awareness. Cronbach's alpha is the most common measure of internal consistency when a study uses multiple Likert questions in a survey. The Cronbach's alpha for the seven SA items was 0.891 and the corrected item-total correlation for each item was > 0.30 , demonstrating high internal consistency.[206] High internal consistency means the respondents who tended to select low (vs. high) scores for one item also tended to select low (vs. high) scores for the others.

Second, the investigator assessed the indirect SA measures (Q/q 1-7) and one direct SA measure (q 6a). The study provided preliminary evidence that the group significantly increased the total SA (2.29 vs. 4.57, $p<0.001$), Level 1 SA (1.8 vs. 4.6, $p<0.001$), and Level 2 SA (2.0 vs.4.5, $p<0.001$) when used the GUI. When comparing the unit vs. non-unit staff, the unit staff had a higher baseline median total SA than the non-unit staff (2.57 vs. 1.29). The non-unit group demonstrated not only a higher total median post-test SA but also a greater magnitude of change in Level 2 SA than the unit staff (a difference score, 4 points vs. 2 points). This can be explained by several factors including, for example, limited access to patient records among the non-unit consulting group or a practice that does not perform daily monitoring of the hospital

unit epidemiological status by infection preventionists. In contrast, the unit-based nurses have face-to-face meetings where they discuss the ongoing issues and plans for the day. The unit-novice staff reported a much higher baseline SA than their experienced peer did. In contrast, the experienced participants in both groups (unit-based and non-unit based) showed much higher SA scores after using the GUI.

The groups demonstrated the lowest baseline median SA scores (1.00) for the use of antibiotics, the receipt of chlorhexidine bathing, and the conditions (circumstances) when the risk of ABRO transmission may be high.

With the GUI, the participants significantly increased their awareness about antibiotics use. As discussed in Chapter 3, the use of antibiotics is a considerable contributing factor to antibiotic resistance.[145, 181, 182] The data on antibiotics administration are readily available in EHRs and easy to capture unlike accurate diagnoses of infections. Representing antibiotic data within the local epidemiological context may address situational awareness needs of a different stakeholders group (e.g. antibiotics stewardship). Therefore, the future study should explore the GUI content in a broader group of HCPs.

The findings revealed a lack of awareness (median= 1.00) about the receipt of chlorhexidine bathing, which may relate to the quality of infection prevention and control practice. Theory of Goal Setting and Team Performance postulated that more frequent and specific feedback for a given task leads to a higher performance because individuals invest more resources while comparative feedback facilitates coherent process planning. The literature showed that the availability of feedback on compliance with infection prevention guidelines was strongly associated with the Hawthorne effect.[207-209] The proposed GUI can deliver real-time feedback to individuals, facilitate priority management, and, eventually, increase the compliance with infection prevention and control practices. The study showed the increase in the team SA score for this questionnaire item (median=5.00) with the use of GUI.

The essential finding of this study was the detected improvement in Level 2 SA (median difference=2.50) after introducing the GUI. The participants assessed their baseline SA regarding the high-risk for infection transmission situations as relatively low (median=2.00). The post-test results showed a

significant increase of the team's SA of such situations (median=4.50). Seventeen out of 19 participants correctly showed the high-risk locations using the GUI.

The all participants (n=19) demonstrated high baseline score (median=4.00) for “a need to know their occupational exposure to ABRO” (range 2, 5). After introducing the GUI, the post-test scores increased (median=5.00, range 3, 5; $p=0.033$). This finding informs that awareness about the occupational risk of exposure to ABROs may add value to infection surveillance. Tracking and sharing the information about individuals' exposure to ABROs may leverage compliance with infection prevention and promote innovative solutions. Targeting host pathways and reducing staff exposure to ABROs with methods other than hand hygiene may be effective for infection and outbreak management. The verbal post-test feedback provided the additional insight about the need to know the extent to which HCPs are exposed to ABROs. The participants communicated that with the GUI-based information they recognized “hospital environmental dangers” leading to a prospect to “protect myself better”. It appears that the GUI supports Level 2 SA about the risk of exposure to ABRO via the explicit image indicating the areas of high risk for exposure. Overall, the participants endorsed that the GUI-based information representation makes the infection prevention and control meaningful to them.

As the study showed, the less experienced staff members perceived their awareness at much higher level when comparing to the more experienced staff. This could be explained by level of experience. The experienced group of healthcare practitioners, those who worked more than five years in healthcare, showed high consistency in their EHR vs. GUI responses in spite of their membership status.

The usability measures showed that 70% of the respondents perceived the GUI as superior to the EHR in its capability to provide meaningful and easily understandable information on infection transmission risks and exposures. During the verbal post-test discussion, the participants characterized the GUI as the better means to alert the staff about the infection risks than the current flagging method for carriers of ABRO in the EHR. The infection preventionists expressed their strong interest in the GUI by asserting that the unit-population surveillance information displayed with the GUI “makes lots of sense” for understanding the unit epidemiology. At the same time, few responders rated the GUI-based usability equivalent to the EHR. It appears that the GUI training material was somewhat challenging for the less

experienced staff, which may require either more time for training or a different method of information representation. The duration of training (less than 10 minutes), level of experience, and complexity of the information could affect these findings.

The verbal feedback provided additional insight on the GUI value-added contribution to practice. The infection preventionists sparked a discussion on tactics, which are considered the best practice, in application to the data displayed with Map 1(the GUI). For example, they described the need to approach patients in a particular order: starting patient care with non-infected patients and then approaching the infected patients. Another tactic communicated by the infection preventionists concerned patients arrangement on the unit: e.g., so-called patient-HCP cohorting rules are applied in some hospitals in order to reduce the risk of polyclonal outbreaks. Visualization of the patients' infection states and their locations in the unit would enable the assessment of patient arrangement safety for timely adjustments.

Finally, many participants asserted that the GUI motivated them to practice “better protection” from ABROs. In addition, one participant suggested to deliver the GUI information via Bluetooth at time of approaching “high risk zone”. The non-unit based responders, such as consulting staff, acknowledged their desire to have the GUI-based information prior to the patient care.

The study has some strength and limitations.

Strengths

The aim of the GUI was to enable HCPs to rapidly gain a high level of understanding regarding the infection transmission “hotspots” and individuals at high-risk of exposure to ABROs. The strength of this development was its focus on the user-centered design. The investigator applied the principles of situation awareness-oriented design for the specific context of use and the rules of graphical design. According to the International Organization for Standardization (ISO) 9241-11 (1998), for visual display terminals, usability is defined as “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. [210] The study pilot evidence showed that the proposed GUI has the potential to address the infection prevention and control challenges.

This study successfully utilized the process tracing (PT) approach with the use of simulated incident for the pilot measurements of the team SA. This approach is recommended for “highly repetitive tasks that lack clear feedback” and do not instantaneously result in dramatic or memorable incidents. The research study found that PT appears suitable for the infection prevention and control domain.

The early evaluation of the GUI permitted the use of both low fidelity testing and self-rating technique for measuring SA. The main advantages of the self-rating techniques include the ease of use, rapid collection of data, and low cost. Although the investigator managed to acquire relatively rich information with this pilot evaluation, the future study needs to explore objective measures of SA with rigorous research design (e.g., randomization, case-control). The future study can test the following objective measures, time on task and degree of errors (accuracy). Situational Awareness Global Assessment technique (SAGAT) may be employed as the effective means of assessing both individuals and teams in a human simulation environment.[211] SAGAT will help better understand to what extent the GUI aids or undermines healthcare practitioner ability to perform (e.g. make decisions, deliver tasks, comply with guidelines, and search information).

This evaluation also took advantage of the survey design, such as economy, rapidity of turn-around in data collection, and ability to identify attributes of a population from a small group of individuals.[212, 213] There are several types of surveys used in healthcare survey research design, including epidemiological surveys, surveys on attitudes to and perceptions of a health service or intervention, and questionnaires assessing knowledge on a particular issue or topic.[214] The investigator created the questionnaire for measuring individuals’ perceptions. The survey-driven data collection method was feasible for this pilot, exploratory research. It also allowed the investigator to derive insights for further GUI development and make a decision to continue this work.

Weaknesses

The study has some limitations. It needs to be acknowledged that the pre-post study design, convenience sampling method, small sample size (n=19), and single setting generally work as limitations for generalization of the results. A more rigorous study design would have a control group with randomized assignment for EHR vs. graphical GUI.

Another problem relates to the use of SA self-rating methodology. The important problem of this technique is that users, including both experts and non-experts, are not always aware of what they do not know. Therefore, the disadvantage of SA self-rating technique includes its subjective nature due to the possible influence of perceived performance.

6.11. Study Contribution

In 2013, the World Economic Forum announced that antibiotic resistant infections became a serious public health threat. The investigator attempted to address this challenge by translating the infectious outcomes and its established antecedents (risk factors) into operational practice with the GUI in order to enable innovative tactical and strategic decision-making. Many poor decisions have been attributed to poor SA; therefore, more SA seems beneficial for performance and outcomes.[61]

The study demonstrated how the SA-oriented approach increases SA in the infection prevention domain. By integrating the knowledge from the different fields, such as Image Theory, SA-oriented system design, risk assessment, epidemiology of nosocomial infections, and Theory of Goal Settings in Teams, the investigator was able to design the novel graphical representation of the information and test it with the use of empirical EHR data.

First, the study showed that the EHR data has a great potential for solving population-level problems, coordinating the distributed team members' communication, and motivating the staff members to enhance their performance. The latent EHR data buried in non-structured text need to be abstracted for the meaningful use. The integrated displays may present the aggregated, de-identified population data to healthcare practitioners who, otherwise, do not have access to all patients' records.

Second, the proposed GUI showed that it is capable to enable the team to achieve much higher SA in seconds. The study provided preliminary evidence that the proposed design met the multi-operator design principles.[51] The GUI accomplished to build a common operational picture that can support team communication and transmission of different comprehensions and projections across and within positions.

For the first time, the EHR data were presented in a manner that made Level 2 SA easier for the users. The GUI successfully captured the users' attention by presenting the critical cues. Although the training was very brief, the staff quickly realized that some locations may be at higher risk for infection transmission and some individuals may have a higher risk of exposure to ABRO than the others. Furthermore, the study revealed that the visualization method could motivate individuals to improve infection prevention in order to reduce their exposure to occupational hazards, such as ABROs.

6.12. Summary

The study findings indicate that the GUI design significantly increased HCPs' situational awareness. The magnitude of this improvement was greatest in those who did not have access to all patient records and who were less experienced. In conclusion, healthcare data visualization may solve the problem of cognitive complexity caused by fragmented, granular data in EHR systems and healthcare dynamic environment. Development of innovative data visualization approaches that enable HCPs to recognize risks of infection transmission, properly allocate limited resources, and maximize benefits of infection prevention in specific epidemiologic situations is desirable. Visualized hospital population data for specific diseases or medical conditions would be important in emergencies when the intensity of work and monitoring needs rapidly increase. Specifically, visualization of the mapped data provides instantaneous answers, making the groups and potential explanations appear. The analysis of the empirical data and the SA measurements helped the investigator to understand the scope of information that support Level 1 SA and Level 2 SA. The research provides a new form of medical knowledge representation for spatial population-based decision-making within enclosed environments.

CHAPTER 7: CLOSING REMARKS

Antibiotic resistant (ABR) infections are an emerging public health threat, exacerbating the challenges with infection control. Hospitals are a major source for the emergence and selection of multidrug-resistant organisms.[5] Properties of healthcare setting significantly contribute to the spread of resistant infections attributed by population density, prevalence of diseased cases, proximity to diseased cases, clustering of contacts, repetitions of contacts, and contamination of personnel, environment, and equipment. Constantly changing patterns in spatial distribution and prevalence of infectious cases, clustering of contacts, and frequency of contacts may compromise the effectiveness of infection prevention and control. It is realized that traditional approaches to infection control based on education and reporting of hospital-acquired infection (HAI) rates often fail to ensure reliable compliance and real-time problem solving. This Ph.D. work attempted to address the national priority call set by the Centers for Disease Control and Prevention in 2013 for reducing antibiotic-resistant infection rates through the **development of the SA-oriented information system** for coping with healthcare-associated infection transmission.

In complex, dynamic sociotechnical contexts, individuals engage in **knowledge-driven, context-sensitive choices** from alternatives in order to achieve goals.[215] Situation awareness is a fundamental construct driving human decision making in complex, dynamic environments.[216] By creating designs that enhance an operator's awareness of what is happening in a given situation, decision making and performance can improve dramatically. Introduction of new technologies into healthcare operations and a massive increase in systems and displays generating large amount of granular data and information have adversely affected HCPs' cognitive activities and, thus, situational awareness. Eccles et al. stated that information consumes the attention of its recipients; hence, a "wealth of information creates a poverty of attention and a need to allocate that attention efficiently among the overabundance of information sources that might consume it".[217]

Situation awareness-oriented system design helps to allocate operators' attention to critical informational cues. This Ph.D. work applied the SA-approach for developing the GUI that enables HCPs to

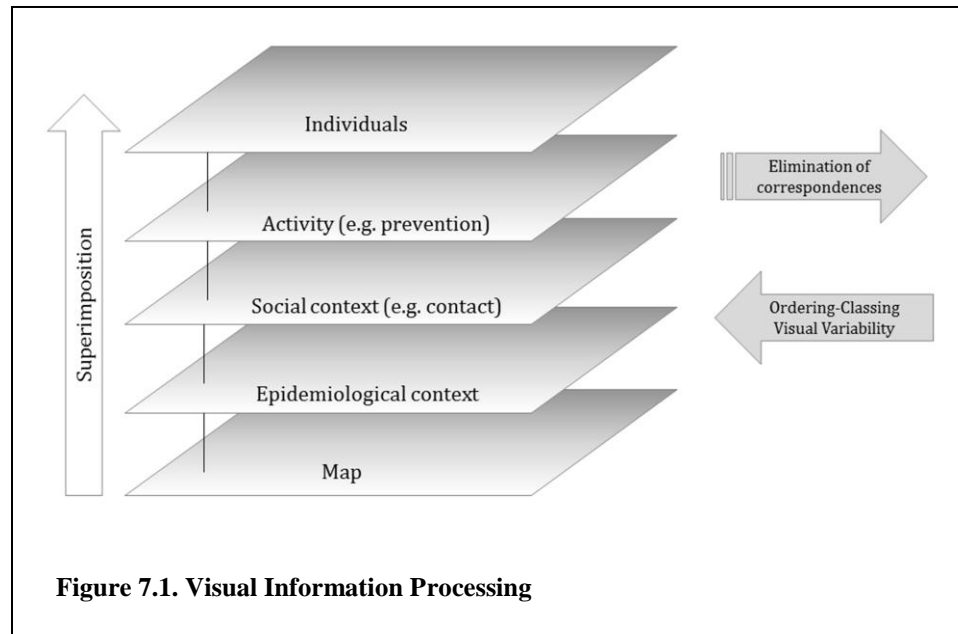
easily and promptly identify the risks for infection transmission. The investigator implemented the following processes:

1. **Contextualization of data:** a process of transforming available expert knowledge from published research in a specific (e.g., epidemiology) domain into an SA-model to deliver critical cues to users in order to support users' Level 1 SA (perception) and Level 2 SA (comprehension);
2. **Recovery of information from EHR:** a process of identifying and extracting the useful data latent in the EHR text and non-text formats for transcribing it into a new format, making the expertise more accessible and usable by both experts and non-experts' tasks and decisions; and
3. **Transcription of the information into the new format(s):** a process of developing an effective visualization of the aggregated data set aiming at reducing user's cognitive complexity with potential to support decision-making and/or create new knowledge.

This research study showed that the Situation Awareness-Oriented Design principles appear practical for supporting healthcare users' Level 1 SA and Level 2 SA. The research study also showed that EHR systems represent a valuable source of latent data for improving situational awareness. **Integrating** data associated with the critical cues within a specific context can reduce the cognitive overload effect, allow people to effectively perceive the information, and gain a high level of understanding for decision making. **Effective visualization** of that information enables users to quickly recognize the significance of events in a complex stream of events. The research also indicated that the **integration of EHR data and graphical facility layout** (a map) may emerge into the essential interface between a human user and dynamic healthcare environments for effective optimization of the disease management. Such interface may minimize cognitive complexity by stratifying a geographic area into risk zones at the rate of environmental changes, which may determine the rapidity with which decisions need be made.

The ABRITSA conceptual model, which embodied the GUI content, included the five conceptual layers of data: (1) the map, (2) the epidemiological context, (3) the social context, (4) the activity context, and (5) the individuals (Figure 7.1). The epidemiological and social layers represented the hospital "environmental" changes, such as spatial distribution and prevalence of diseased and non-diseased cases.

The “activity” layer represented activities or interventions documented in the EHR. The “individuals” layer represented patients and HCPs affected by this environment.



The study preliminary results have shown that the developed GUI significantly increased HCPs’ perception and comprehension of the areas at high-risk for ABR infection transmission in a medical-surgical unit, the subjects at high risk of exposure to ABR microorganisms, and the variance in compliance with infection control. The study concluded that the GUI appears a more effective approach for improving SA, defined as the recognition of the infection transmission risks (Level 1 SA) and a comprehension of these risks in a context of patient and healthcare practitioners’ safety (Level 2 SA), than the current practice. Finally, it is important to summarize the lessons learned about *data visualization*.

A Need for Novel Forms of Healthcare Data Representation

Lessons Learned

- Maps can be seen as an effective interface between a human user and EHR data to quickly identify clinically significant events. The visual information processing described by Bertin permits the situational awareness design.

- The main elements of the visual information processing include: (a) the elimination of certain correspondences, (b) the visual ordering and classing, and (c) the superimposition of images. (Figure 7.1).
- The effectiveness of the graphically processed information depends on the choice of visual variables that efficiently facilitate visual selective and associative perception;
- The utilization of retinal variables for representation of the ordered qualitative components is the basis for graphical information processing;
- The effective visual information representation reduces information conceptual complexity and increases the speed of discovering the groups and exceptions.

Designed in conjunction with the unit-based map(s) information, the GUI can be used by hospital administration, physicians, infection preventionists, unit managers, risk managers, front-line staff, quality improvement specialists, and public health practitioners. This approach will improve communication within and between teams, with critical information transmitted to all affected stakeholders in a readily understandable and actionable format.

Future Directions

Achieving better patient outcomes at lower cost with the use of health IT is still a challenge. Human-centered tools need to support active organization of information, active search for information, active exploration, reflection on the meaning of information, and evaluation and choice among action sequential alternatives.[215]

Rapid application development (prototyping) is critical for studying Level 3 SA. Level 3 SA is important for allowing operators to be proactive rather than reactive in the decision-making process.[218] This level was described as “now what?”[219] Therefore, the future research needs to explore how the GUI facilitates Level 3 SA with rigorous design methods. Specifically, the future research has to explore the extent to which the novel GUI aids tactical decision-making for infection prevention in different users. In addition, there is a need for a further analysis of the interface design features, data granularity, and alternative data sources.

From a practical perspective, it is important to have technologies investigated for their potential applicability to solving patient safety problems. From a theoretical standpoint, the concepts that drive the development of new technologies also must be identified. The experimental approach based on logics and concepts developed by valid, existing theories (e.g., Theory of Goal Settings in Teams) as well as early technology evaluation based on objective and subjective methods (e.g., SAGAT) may solve these tasks.

APPENDIX A: THE QUESTIONNAIRES

1. The questionnaire designed for the unit staff pre-test, cont.

The IPSA Survey v.1.0. 03/01/2015 Author: Kettelhut V. V.

The Infection Prevention Situational Awareness Survey I- 5N

Dear Participant,

This survey is **anonymous**; your individual answers will not be shared with anyone.

Date _____

Are you authorized to access all records of the patients who are bedded on 5 N?

☐ Yes ☐ No

Are you a permanent staff member on 5 North?

☐ Yes ☐ No

Please indicate if the statement below is true or false.

Carriers of antibiotic resistant bacteria (**carriers of ABR bacteria**) are the patients who have at least one of these bacteria MRSA, VRE, ESBL, MDRO, etc.:

☐ True ☐ False

1. Please rate your awareness level of the patients who are carriers of ABR bacteria when you first approach them during the shift:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

2. Please rate your awareness level of the locations of the carriers of ABR bacteria on the unit during your shift:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

☐ I do not need to know about it if it's not my patients.
☐ Not applicable

3. Please rate your awareness level of the types of ABR bacteria present on the unit during your shift:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

☐ Not applicable

4. Please rate your awareness level of all the unit patients who receive antibiotics on the unit during your shift:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

☐ I do not need to know about it if it's not my patient.
☐ Not applicable.

5. Please rate your awareness level at the beginning of your shift of your patients who did not receive chlorhexidine bathing:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ N/A
Lowest Highest

6. Please rate your awareness level of the circumstances when the risk of transmission of ABR bacteria may be greater in some areas on the unit than others:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

☐ This knowledge is outside of my specific tasks.
☐ Not applicable.

7. Please rate your awareness level of your potential risk of exposure to ABR bacteria during any of your shift:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

8. Would it be beneficial or important to you to be aware of your risk of exposure to ABR bacteria?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Not at all Very important

Other, specify: _____

9. Please identify your current role:

Care Technician ☐
Nurse (role: _____) ☐
Infectious Disease Physician ☐
Infection Preventionist ☐

Other, specify: _____

10. How many years have you worked in healthcare?

Less than one year. ☐
One to five years. ☐
More than 5 years. ☐

the unit staff post-test

The IPSA Survey v.1.0. 03/01/2015 Author: Kettelhut V. V.

The Infection Prevention Situational Awareness Survey II-5N

Dear Participant,

The goal of this part of the survey is to assess the effects of the proposed interface design on your awareness about the risks for antibiotic resistant infection transmission.

WITH THE USE OF MAP 1 AND MAP 2, PLEASE RATE YOUR AWARENESS LEVEL OF:

1. The unit patients who are carriers of ABR bacteria on a given day (Map 1):

Lowest ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Highest

2. The locations of the all carriers of ABR bacteria on the unit (Map 1):

Lowest □ 1 □ 2 □ 3 □ 4 □ 5 Highest

3. The types of ABR bacteria the unit patients present (Map 1):

□ 1 □ 2 □ 3 □ 4 □ 5

Lowest Highest

4. The unit patients who receive antibiotics (Map1):

Lowest ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Highest

5. The unit patients who did not receive chlorhexidine bathing (Map 1):

Lowest ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Highest

6. Please rate your awareness level of the circumstances when the risk of transmission of ABR bacteria may be much greater in some areas on the unit (Map 1):

Lowest ☐ 1 ☐ 2 ☐ 3 ☒ 4 ☐ 5 Highest

6. a. Using Map 1, please provide at least one ward number where the risk of infection transmission may be elevated:

AND please mark all applicable risk factors that make this location risky:

Patient is a carrier of ABR bacteria	<input type="checkbox"/>
Patient has a significant bacterial load	<input type="checkbox"/>
Patient represents "high contact patient"	<input type="checkbox"/>
Patient did not receive chlorhexidine bathing	<input type="checkbox"/>
Patient receives antibacterial treatment	<input type="checkbox"/>
Patient room is close to a carrier of ABR bacteria	<input type="checkbox"/>

7. Using Map 3, please rate your awareness level of the 5 North staff members who may experience a greater risk of exposure to ABR bacteria than others:

Lowest □ 1 □ 2 □ 3 □ 4 □ 5 Highest

8. Would it be beneficial or important for the unit staff to be aware of their risk of exposure to ABR bacteria?

Not at all ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Very Important

Other, specify: _____

9. Please answer the following statements to reflect your opinion about how different systems (EHR vs. the new interface) affect you:

The new interface design informs me about the risks for antibiotic resistant infections in a quick way:

☐ Yes ☐ No

The current EHR system informs me about the risks for antibiotic resistant infections in a quick way:

☐ Yes ☐ No

10. The visualizations, such as “red color”, “large red glow” and “yellow dot” on Map 1 strongly prompts my alertness about the infection transmission hazards:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
 Strongly Disagree Strongly Agree

11. The visualized locations where the chlorhexidine bathing is deficient would help the staff to coordinate their daily planning efficiently:

Strongly Disagree □ 1 □ 2 □ 3 □ 4 □ 5 Strongly Agree

☐ Not applicable.

PLEASE RATE THE TRAINING MATERIALS.

12. The training material was easy to understand:

Strongly Disagree Strongly Agree

Thank you very much for your participation!

Please let us know if you would like to have the results of this survey.

☐ Yes ☐ No

2. The questionnaire designed for the non-unit staff pre-test, cont.

The Infection Prevention Situation Awareness Survey I-IP

Dear Participant,
This survey is **anonymous**; your individual answers
will not be shared with anyone.

Date _____

Are you authorized to access all records of the
patients who are bedded on 5 North?

☐ Yes ☐ No

PLEASE ANSWER THE QUESTIONS BELOW.

Please indicate if the statement below is true or false

Carriers of antibiotic resistant bacteria (carriers of ABR
bacteria) are the patients who have at least one of these
bacteria MRSA, VRE, ESBL, MDRO, etc.

☐ True ☐ False

1. Please rate your daily awareness level about the
patients who are carriers of ABR bacteria on 5 North:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ I do not track the prevalence cases on a daily basis.
☐ Not applicable.

2. Please rate your daily awareness level about the
locations of the all carriers of ABR bacteria on 5 North:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ Not applicable.

3. Please rate your daily awareness level about the types
of ABR bacteria present on 5 North:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ Not applicable.

4. Please rate your daily awareness level about the
patients who receive antibiotics on 5 North:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ This task is outside of my daily duties.
☐ Not applicable.

5. Please rate your awareness level about the unit patients
who did not receive chlorhexidine bathing:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ Not applicable.

6. Please rate your daily awareness level about the
circumstances when the risk of transmission of ABR
bacteria may become much greater in some areas on the
unit:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

☐ Such knowledge is outside of my duties.

7. Please rate your daily awareness level about the unit
staff members who may experience a greater risk of
exposure to ABR bacteria in comparison with others:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Lowest Highest

8. Would it be beneficial or important to the unit staff to be
aware about their individual risks of exposure to ABR
bacteria?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Not at all Very important

Other, specify: _____

9. Please identify your current role (all that apply):

Care Technician ☐
Nurse (role: _____) ☐
Infectious Disease Physician ☐
Infection Preventionist ☐

Other, specify: _____

10. How many years have you worked in healthcare?

Less than one year. ☐
One to five years. ☐
More than 5 years. ☐

the non-unit staff post-test

The Infection Prevention Situation Awareness Survey II-IP

Dear Participant,

The goal of this part of the survey is to assess the effects of the proposed interface design on your awareness about the risks for antibiotic resistant infection transmission.

WITH THE USE OF MAP 1 AND MAP 2 PLEASE RATE YOUR AWARENESS LEVEL ABOUT:

1. The unit patients who are carriers of ABR bacteria on the unit on a given day (Map 1):

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

2. The locations of the all carriers of ABR bacteria on the unit (Map 1):

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

3. The types of ABR bacteria present on 5 North on a given day:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

4. The patients who receive antibiotics on the unit (Map 1):

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

5. The unit patients who did not receive chlorhexidine bathing (Map 1):

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

6. Please rate your awareness level about the circumstances when the risk of transmission of ABR bacteria may become much greater in some areas on the unit:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

6.a. Using Map 1, please provide at least one ward number where the risk of infection transmission may be elevated:

AND please **mark** all applicable risk factors that can make this location risky:

Patient is a carrier of ABR bacteria ☐
Patient has a significant bacterial load ☐
Patient represents "high contact patient" ☐
Patient did not receive chlorhexidine bathing ☐
Patient receives antibacterial treatment ☐
Patient room is close to a carrier of ABR bacteria ☐

7. Using Map 3, please rate your awareness level about the 5 North staff members who may experience a greater potential risk of exposure to ABR bacteria than others

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Lowest Highest

8. Would it be beneficial or important to the unit staff to be aware about their individual risks of exposure to ABR bacteria?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Not at all Very important

Other, specify _____

9. Please answer the following statements to reflect your opinion about how different systems (EHR vs. the new interface) affect you:

The new interface design informs me about the risks for antibiotic resistant infections in a quick way:
☐ Yes ☐ No

The current EHR system informs me about the risks for antibiotic resistant infections in a quick way:
☐ Yes ☐ No

10. The visualizations, such as "red color", "large red glow" and "yellow dot" on Map 1 strongly prompts my alertness about the infection transmission hazards on 5 North:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Strongly Disagree Strongly Agree

11. The visualized locations where the chlorhexidine bathing is deficient would help the staff to coordinate their daily planning efficiently:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Strongly Disagree Strongly Agree
☐ Not applicable.

PLEASE RATE THE TRAINING MATERIALS.

12. The training material was easy to understand:

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
Strongly Disagree Strongly Agree

Thank you very much for your participation!

Please let us know if you would like to have the results of this survey.

☐ Yes ☐ No

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