Final Report

Title: Human Factors Considerations in the Design and Implementation of Telemedicine Integrated Ambulance-Based Environments for Stroke Care

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1. ABSTRACT

Purpose: We investigate the cognitive demands, workload, workflow, and communication of geographically distributed caregivers delivering stroke care in ambulance-based telemedicine.

Scope: This project investigated the use of a telemedicine system for evaluating a stroke patient in an ambulance with a geographically distributed caregiving team of a paramedic, nurse, and neurologist.

Methods: Simulated stroke sessions were conducted with care providers, who were asked to complete a survey to measure workload, usability, and teamwork and who participated in an interview to understand how telemedicine changed workflow and demands of the caregiver. Based on the semi-structured interviews and observational studies, a Task Analysis was developed, and subsequently, a heuristic evaluation was conducted to determine the usability issues in the telemedicine user interface. This was followed by a qualitative analysis to determine the sources of disruption and a Systematic Human Error Reduction and Prediction Approach to determine the possibility of human error while providing care using the telemedicine work system.

Results: Barriers to the use of telemedicine systems included frustration with equipment and training of care providers increasing cognitive demands, loss of personal connection of neurologists with patients, and physical constraints in the ambulance. Facilitators were more common, including live and visual communication increasing teamwork and efficiency, ease of access to specialists, and increased flexibility. Seat size, arrangement of assessment equipment, location of telemedicine equipment, and design of telemedicine camera were among the factors that impacted telemedicine-related disruptions. Several remediation strategies were identified, including automation of task structure and audio/visual improvements to support communication.

Keywords: Telemedicine, prehospital care, human error, usability, provider-to-provider communication

2. PURPOSE

Strokes are one of the most serious healthcare issues in the United States: they represent the fifth leading cause of death, resulting in 1 death about every 4 minutes and annually costing $34 billion in health care, medication, and lost work.[1,2] To improve stroke outcomes, healthcare professionals seek to minimize the time to treatment to restore blood flow to the affected tissue. For example, strokes caused by a blood clot (ischemic strokes) result in brain tissue death as blood cannot circulate to the affected area. Thus, the earlier patients receive treatment, the more likely they are to have improved clinical outcomes and reduced long-term disability and treatment complications.[3] Telemedicine, the use of telecommunications technology to remotely connect trained specialists to patients, has been recommended by the American Heart Association and the American Stroke Association for improving stroke care.[4] Indeed, research shows that telemedicine has improved patient triage, increased accuracy of diagnosis, and most importantly, reduced time to treatment.[5,6] This quick access to stroke specialists or neurologists afforded by telemedicine improves the process of correctly diagnosing a stroke.[7] Telemedicine further coordinates receiving hospitals to allow for expedited care as ambulance-based telemedicine can permit stroke consultations enroute. This can decrease time between first provider contact and definitive therapy, as specialists can rapidly identify and triage stroke patients.

To provide more immediate care, ambulance-based telemedicine can permit stroke consultations enroute to the hospital, and rapidly identify and triage stroke patients to decrease the time between first provider contact and definitive therapy.[6,8] These ambulances are equipped with inexpensive telemedicine systems consisting of a laptop connected to the Internet through a wireless router combined with a web-camera and a speaker for physician monitoring of the patient and consultation with the attending Emergency Medical Technician (EMT)/pre-hospital provider. As this description suggests, a telemedicine-integrated, ambulance-based caregiving environment is a complex socio-technical system involving multiple agents with different goals and complex evolving technologies and processes.[6,9] It is managed by a collaborative and distributed team consisting of pre-hospital providers, emergency medicine nurses, and physicians whose interactions must be considered while implementing an ambulance-based telemedicine system, important as these healthcare providers are required to operate multiple systems, including the telemedicine system, in a constrained, high-stress setting, adding to the complexity of the caregiving process.[6,10] The overall aim of this proposal was to i) understand the demands placed on EMTs and caregivers while providing care ii) understand the potential user-errors (system failures due to the limitations of personnel operating the telemedicine system) and design-errors (human errors due to the telemedicine-integrated system design), and iii) develop optimal workflow, guidelines, and recommendations for an enhanced system design in a telemedicine-integrated ambulance-based setting. Observational studies and semi-structured interviews were conducted with pre-hospital providers, nurses and physicians focusing on workflow, physical space constraints, communication patterns, software system usability, and overall teamwork in order to evaluate the telemedicine-integrated ambulance-based system's use, appropriateness, effectiveness and performance post pilot-implementation.

3. SCOPE

The typical stroke care process with ambulance-based telemedicine includes an Emergency Medical Service (EMS) conducting a quick assessment of the patient and alerting a receiving hospital of the incoming patient and their information. Then once in the ambulance and connected to the telemedicine system, a neurologist conducts a detailed assessment until the patient arrives to the Emergency Department (ED) and admitted. The neurologists' awareness is of paramount importance for this system to be effective as they neurologist must gather information from the patient and paramedic to maintain an understanding of patient status and develop a diagnosis and care plan. Development and maintenance of this awareness is necessary especially for ischemic strokes, which account for 87% of all strokes, as they are treated with a life-saving treatment referred to as a tissue plasminogen activator (tPA).[1] This treatment has multiple conditions and contraindications affecting its use, the most common being that it must be administered within 4.5 hours of stroke symptom onset.[11] As such, an awareness of the time from the symptom onset must be maintained. Time is not the only factor that neurologists must be aware of, a hemorrhage, high blood pressure or the use of blood thinners all prohibit a patient from receiving tPA.[12] In addition, mimics for strokes such as low blood sugar or seizures must be ruled out.

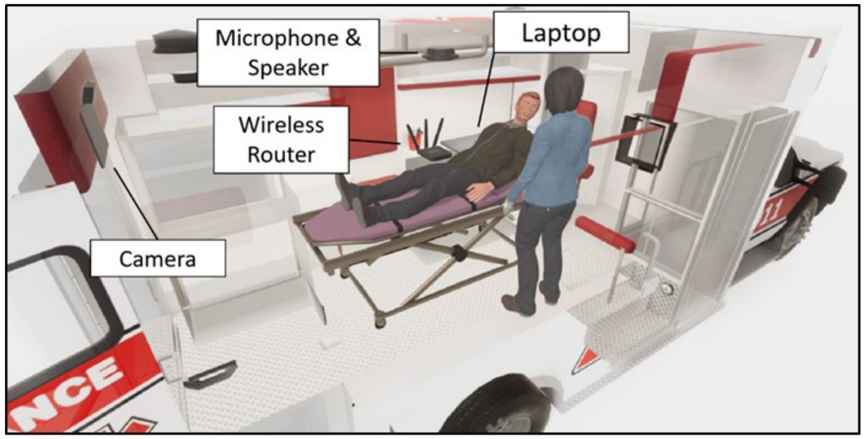

Figure 1. Schematic of the **pilot** telemedicine system implemented in the Georgetown County Fire EMS ambulance for stroke care

While telemedicine has been studied extensively as a tool for improving time to treatment and ultimately patient care outcomes, the current research lacks an understanding of the effect of this system on the caregivers involved, the neurologist, the nurse at the receiving hospital and the paramedic in the ambulance, all of whom coordinate the patient care. To address this issue, a small rural county in southeastern United States in conjunction with a tertiary care hospital has implemented a pilot telemedicine system (shown in Figure 1) called REACH in their ED and ambulances which facilitates earlier contact with a neurology specialist, which the rural county hospital does not have access to on site. The REACH telemedicine platform serves two functions: as a tri-directional visual communication with the secondary hospital, the tertiary hospital, and the ambulance and as a tool to document information about the patient case[13]. All caregivers have the same interface in REACH, which includes a view of the patient in the ambulance, the hospital, and the neurologist, and an information screen where patient history, vitals, assessment items, imaging, and other information can be accessed.

The specific objectives of this project are to (1) understand the tasks needed to complete a stroke assessment using telemedicine in an ambulance and how those tasks are completed; (2) determine the usability issues in the telemedicine system and the possible errors that could be made; and (3) provide recommendations to improve the telemedicine design to mitigate usability issues and errors. To understand how these recommendations impact the work system, work processes and ultimately outcomes in the healthcare system, the Systems Engineering Initiative for Patient Safety (SEIPS) 2.0 model was used as method to accomplish the third objective in addition to a heuristic evaluation and the Systematic Human Error Reduction and Prediction Approach (SHERPA). SEIPS describes the work system factors in a healthcare system, how they interact to create work processes, how work system factors and work processes impact outcomes, and how outcomes feed back to the work processes and the work system[9]. To accomplish these objectives, a Hierarchical Task Analysis was completed and used as input for the heuristic evaluation and in a SHERPA. It is crucial to analyze how the telemedicine system is used by caregivers because they ultimately determine patient safety and patient outcomes. Subsequent sections detail the approaches used to accomplish the objectives of this study, the data collection and analysis methodologies, the results of the analyses and a discussion including recommendations for ambulance-based telemedicine system design based on the analyses.

4. METHODS

Participants

Participants were recruited through purposive sampling from two major hospitals and a Fire and EMS department in the southeastern United States. Four pilot and nine final observation sessions were conducted with 3 caregivers recruited for each session, a nurse, paramedic, and neurologist. Thus, participants included 13 nurses, 13 paramedics and 13 neurologists, in total 39 caregivers. In addition, an EMT to drive the ambulance during the studies and a standardized patient to allow for a simulated stroke were recruited for each session. Paramedics and nurses were recruited by their supervisors using word of mouth and the neurologists by email. The only inclusion criterion for these participants was their occupations: paramedics were currently employed at a rural southeastern county EMS, nurses were on staff in a major hospital in the same rural southeastern county, and neurologists were completing a telehealth rotation in a major hospital in the Southeast.

Procedure

Participants were met the day of the study and informed that the purpose of the research was to obtain information to help understand the telemedicine system such that recommendations could be developed for its improvement; they were also told that the interviewer was completing this research for her dissertation work. One researcher was located at the major hospital with the neurologist participants, and another at the rural county hospital managing the paramedic, patient, and nurse as they completed the study. All participants completed their normal workflow during the observation, which was audio and video recorded. A portion of this study was conducted in an active Emergency Department (ED) to simulate real noise conditions as close as possible. As such other nurses or patients were in the area during these observations. Participants then completed a Qualtrics survey, and the interviews were conducted in person after this survey was completed.

Measures

The National Aeronautics and Space Administration Task Load Index (NASA-TLX) was used to measure caregivers' perceived workload during the simulation.[14] This survey measures 6 sub-scales of workload--Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration--on a scale from 0 to 100, which are then combined into a Total Workload and weighted based on importance for each participant. The International Business Machine Corporation Computer System Usability Questionnaire (IBM-CSUQ) was used to measure their perception of the usability of the telemedicine system.[15] This survey measures usability based on the level of agreement to 16 statements on a scale of 1 to 7, an overall score and 3 subscales (System Usefulness, Information Quality, Interface Quality). The Team Effectiveness scale was used to measure quantitatively how individuals felt their team worked together.[16] This survey measures the level of agreement to 8 statements on a scale of 1 to 5, with each statement measuring a different aspect of teamwork, such as team member commitment or satisfaction with performance; the agreement rankings are averaged for an overall measure of team effectiveness. Twenty-seven interviews were conducted with each of the 3 types of participants (paramedic, nurse, and neurologist) for each of the 9 observation sessions completed, and 10 interviews were conducted with pilot participants as some sessions involved repeated caregivers. Notes were taken during the interviews to guide additional questions or to focus the thematic analysis that would subsequently be conducted. Questions were adapted from an interview protocol developed by the Center for Quality and Productivity Improvement at the University of Wisconsin-Madison, and questions specifically pertaining to teamwork, distributed cognition, and physical environment changes were added to the protocol. This question list was then pilot tested with one neurologist for length and repetition, then tested after pilot observations. After these tests several repetitive questions were removed, some were reworded for clarity, and some that did not pertain to certain roles (such as physical constraints of the ambulance) were removed such that two protocols were made, one for paramedics and one for nurses and neurologists. The interview audio files were transcribed to be analyzed for themes found in the responses.

Analysis techniques

The survey data were analyzed using descriptive statistics for each measurement. Two coders were assigned to descriptively code the interview data to ensure researcher bias did not influence the codes developed, and prior to consensus the researchers assessed intercoder agreement using the Atlas.Ti 8 program. This analysis function in the code management program assesses coder agreement in the use of a single code over all documents using Krippendorff's alpha. Open coding was used to create a code book from the pilot interviews, and once the code book was defined, the two coders used it to classify the responses of the final 27 interviews. Quotes for each descriptive code were summarized and further categorized the themes by caregiving role if the themes deviated, then combined by topic. These themes were further summarized into major and minor themes representing the data, and barriers and facilitators were identified for each theme. A flat structure was used for the descriptive coding, meaning no hierarchical structure was used. The interviews were on average 36 minutes long, and the total audio time for all 27 interviews conducted was approximately 16 hours and 13 minutes. Due to the complex nature of responses and the number of documents to manage, Atlas.Ti 8 was used in all levels of coding.

Development of Hierarchical Task Analysis (HTA)

First, the development of a structure of the tasks including their goals and subgoals was necessary to create the subsequent entire structure of the complex process requiring several caregivers to complete and to serve as inputs in the additional analyses conducted. Based on the observations, an HTA was performed for each role, from the time a caregiver logged on to the telemedicine system to the patient leaving the ambulance after completing a stroke assessment. Given that many steps and protocols either followed a specified order or occurred simultaneously, a clear order was needed to fully understand both how the stroke assessment process should be completed and how the tasks and protocols deviated in various situations. Based on our observations, the researcher was able to list all tasks for all caregivers and establish a beginning and end point for the assessment. A retrospective think aloud protocol was used to detail the thought processes or protocols supporting this order and to identify deviations from the steps listed. After the list was created for each role, the tasks were grouped into goals and subgoals, and protocols were developed to identify how each goal and subgoal were completed based on the tasks. At this stage, the task lists were shared with the caregivers to obtain their feedback. The caregivers corrected the steps in the lists, adding or removing them when necessary and clarifying the protocols. Based on this feedback, a unique HTA diagram was developed for each caregiver role. These role-specific HTAs served as the input for the heuristic evaluation as each role was evaluated separately. To create the input for the SHERPA, the tasks were combined into an overall process to create a Team Hierarchical Task Analysis. Again, the tasks were organized into goals and subgoals and each subgoal was assigned a team member. New protocols were created for the overall process to reflect the timing of the tasks for all caregivers. An additional step identified where teamwork was required and the criterion for determining when the goal was completed.

Heuristic evaluation

To conduct a heuristic evaluation, the simplified task lists of the 3 caregivers were input into an Excel sheet along with the knowledge requirements for each step, given that the evaluators, while experts in the usability heuristics used, may not have had the medical knowledge to complete the tasks unassisted. Nielsen's 10 heuristics, which are standard for this evaluation, were used in this study.[17]

Three experts from Clemson University completed the evaluation (two men, one woman), each with experience in completing heuristic evaluations of other systems and with training in usability and design. These evaluators included one assistant professor from the Human-Centered Computing Department with a Ph.D. in Information Sciences and Technology, and two Ph.D. students, both with a Master of Science Degree in Industrial Engineering. The choice to use three experts was based on Nielsen's recommendations for conducting heuristic evaluations.[18,19] Each evaluator completed the tasks for all 3 caregiver roles--paramedic, nurse, and neurologist--in the REACH system interface, subsequently describing the violations of the heuristics at each step and assigning each a severity on the scale of 0 to 4 developed by Nielsen, with 0 indicating not a usability problem, 1 a cosmetic problem only that does not need to be addressed unless extra time is available for the project, 2 a minor usability problem that is given a low priority for addressing, 3 a major usability problem that is important to fix and thus given a high priority, and 4 a usability catastrophe that is imperative to fix before the product can be released[20]. Each evaluator worked independently to assess all heuristic violations. Once the list was complete, a single researcher compiled all violations, averaging the severity rating for duplicate violations.

Development of SHERPA

The first input for this SHERPA analysis was the HTA developed for the overall process; then all tasks in the subgoals were classified according to a behavior taxonomy developed by Stanton[21] as either Action, Retrieval, Checking, Selection, or Information Communication. Each behavior in a task involved different types of errors, all of which were described and labeled by behavior type according to the SHERPA error mode taxonomy. If multiple error modes could be applied to the task, each was listed. For example, when entering a password to log in, a user could omit the action step or have an incomplete password or wrong password; in this case Action type error modes A7-9 were applied. The consequences and probability of making an error along with the criticality of the error were identified based on the observations and interactions with the caregivers. Probability is measured on a 3-item scale: Low (hardly ever happens), Medium (happens once or twice), or High (happens frequently), with criticality being measured on a similar scale, ranging from Low indicating a non-critical incident to High indicating a critical incident. It was also determined if the user could recover from each error and at which task step. For example, if the patient's name was incorrectly entered during case creation, this error could be corrected later in the step asking for updated patient demographics. Finally, for each error at least one remedy strategy was identified based on four categories proposed by Stanton (2006): equipment, training, procedures, and organizational. The research team adapted these remediation strategies so that they could reasonably be implemented in the healthcare system. The items from the SHERPA technique (error type, error mode, consequence, recovery, probability, criticality, and remediation) were collected in tabular form to organize the information for each bottom level task in the HTA.

Communication and teamwork during telemedicine-enabled stroke care in an ambulance

To analyze the communication structure, tasks in telemedicine stroke care delivery, and disruptions to team communications, recordings of the interior of the ambulance, nursing station, nursing computer screen, neurologist workspace, and neurologist computer screen were created for each simulated stroke observation. These video recordings, which were coded from the time when all clinicians were connected to the telemedicine system to the time when the ambulance arrived at the emergency department, were used as inputs in the Noldus Observer XT program that was used to code the tasks of the paramedic, the flow disruptions, the communication type, and the communication-pairs. Communication events were coded based on a predefined taxonomy to identify the communication-pair and the direction of the communication (e.g., neurologist to nurse) as well as the communication mode (verbal and nonverbal) and type of communication (e.g., give information, receive information). Each communication event was coded individually; for instance, if an action was requested multiple times, each instance was coded separately to identify related issues and disruptions.

5. RESULTS

The results from the analyses, which are presented in the sections below in the order in which they were conducted, detail the structure of the caregiving task and the number and type of issues found within the system.

An overview of tasks geographically dispersed caregivers completed to provide care

The overall process of care for a stroke patient was described by the caregivers. When a person potentially experiencing a stroke calls 911, the local EMS sends one of their ambulances with an EMT and paramedic team to assess the patient. On arrival, they typically conduct a Rapid Arterial oCclusion Evaluation (RACE), a simple 5-item scale used to help identify a possible stroke. Based on the RACE score and the overall evaluation of the patient, the EMT and paramedic move the patient into the ambulance, call the receiving secondary hospital to begin a stroke consult and log on to the REACH program from a laptop in the ambulance. The nurse at the receiving ED creates the patient encounter, and the system alerts the neurologist on call at the tertiary care hospital of the awaiting consult. The paramedic gathers vital information and stabilizes the patient until the neurologist and nurse can be connected. The neurologist obtains more health history and information about the patient and begins an assessment using the National Institutes of Health Stroke Scale (NIHSS). When the ambulance arrives at the secondary hospital, the patient is taken directly for a Computed Tomography (CT) brain scan, which is immediately uploaded to the telemedicine system such that the neurologist can make a treatment decision that may include transfer to the tertiary hospital for more intensive care. However, to evaluate the ambulance-based assessment, the start and endpoints of the telemedicine system use were used to scope the HTA. The HTA was developed first by role and then as an overall process conducted by a team. Overall, the goal of the team process is to care for the patient; however, individually for the nurse and neurologist, this goal takes different forms. The main goal of the nurse is to prepare for the arrival of the patient at the ED, while the neurologist determines the patient care plan. In the overall HTA, the subgoals for the process are distributed among caregiver roles are further described in the published work in *IISE Transactions on Healthcare Systems Engineering.* [22]

Findings from the heuristic evaluation

A total of 129 usability violations were found by the three reviewers for the 3 roles studied: 10 violations for the paramedic role, 69 for the nurse, and 46 for the neurologist. The average severity rating for each role was 3.375 for the paramedic role, 2.28 for the nurse, and 2.35 for the neurologist. The most frequent classification of severity was a minor usability problem with 45 violations rated at this level, followed by 43 violations rated as a major usability problem, 18 as a usability catastrophe, 22 as a cosmetic problem, and only one violation being rated as not a usability problem (1%). When the common violations were merged and severity ratings averaged, there were 123 violations among the three caregiving roles. All heuristics were used, but the most commonly used was the Visibility of System Status heuristic, which accounted for 24% of all violations, followed by Consistency and Standards with 20% and Error Prevention with 15%.

Some examples of violations found in this evaluation are that the distance from the labels to data input were too large, making it unclear which label belonged to each text box; that the interface for selecting consults was confusing as there did not seem to be a difference between active and pending consults, and that the consults and some tabs in the interface were not clearly clickable, inhibiting the function of the interface. The next most violated heuristic was Consistency and Standards. Some examples of these violations include inconsistent use of radio buttons, multiple conflicting data inputs for the same information, inconsistent date formatting, and inconsistent use of bolding and highlighting.

The role tasks with the most violation was the nurse role. Many violations for this role focused on the data formatting as the nurse role had several steps that required text input. Another frequently mentioned violation in this role was focused on the edit button used to change the demographics of the patient after a patient case is created, violating the Visibility of System Status heuristic as it was unclear that the edit button found when hovering over the patient's name, date of birth, and many other pieces of demographic data would allow the user to edit all information in one menu. This required the user to search after selecting the appropriate menu for the information that required updating rather than providing a singular input for that data. Error messages for missing or incorrect information when creating a patient were either not functioning or unclear, violating the Help Users Recognize, Diagnose, and Recover from Errors heuristic. The findings are further described in the published work in *IISE Transactions on Healthcare Systems Engineering.* [22]

Findings from the SHERPA analysis.

The goal of these analyses was to better understand the tasks and process of each caregiver in the system and determine where environment, training, or system design remediations could be provided to address the errors made. This was a first step for the research team to develop system improvements to support the caregivers in using this telemedicine system for stroke assessment. The potential errors found included almost all task types, with 49% being information communication errors, 35% action errors, 10% retrieval errors, 6% selection errors and 0% checking errors. The prevalence of information communication errors can be explained by the fact that most data needed for stroke assessment are collected from the paramedic and patient verbally. As a result, the most common error is miscommunication or not hearing the response to a communicated command. There are also many action errors for tasks involving recording vitals and creating the patient case. No errors were assessed as high probability or high criticality based on the information collected from the RTA; however, these were only assessed based on the task directly affecting the process. Most errors were found to occur at medium probability, and overall, most errors were considered of medium criticality (55%). In addition, 77% of medium probability errors were also considered medium criticality, and 73% of low probability errors were considered low criticality. Almost all errors (90%) were recoverable immediately after they were made, and for the remaining 10%, recovery steps were identified later when a process was repeated, or the error was accessed in later steps. The findings are further described in the published work in *IISE Transactions on Healthcare Systems Engineering.* [22]

Barriers and facilitators to telemedicine use.

Themes identified as barriers to the use of the telemedicine system were issues with the telemedicine system, training and experience, patient interaction changes, and privacy and consult surroundings. Issues in the system was a major theme for both the paramedic and neurologist caregivers, with comments from six of the latter and all paramedic participants contributing to this theme. The source of these issues when using the telemedicine system consistently involved difficulties with the internet connection or device malfunction. Loss of service or spotty and delayed communication as the ambulance moves into an area with a limited data connection can make many processes difficult; for example, it may make patient responses difficult to see or understand or freeze communications between the neurologist and the paramedic and patient. The system is not without its benefits; in fact, facilitators were more frequently found than barriers in these interviews, and even when the barriers described previously were mentioned, they were often followed by a caveat, suggesting that they were insignificant compared to the benefits to the patient and the overall health system. Facilitator themes identified included the ability to view and communicate with the team, efficiency and focus, access to specialist care, workstation and consult space changes, simplistic documentation, and system usability and satisfaction. The findings are further discussed in our published work in the journal, *Applied Ergonomics.*[23]

Communication among care teams during telemedicine-enabled stroke consults in an ambulance.

The majority of all team interactions in telemedicine-enabled stroke care involved verbal interactions among team members. The neurologist, patient, and paramedic were almost equally involved in team interactions during stroke care, though the neurologist initiated 48% of all verbal interactions. Disruptions were observed in 8% of interactions, and communication-related issues contributed to 44%, with interruptions and environmental hazards being other reasons for disruptions in interactions during telemedicine-enabled stroke care. We also analyzed the findings from the observational studies to understand the nature and source of disruptions in an ambulance during the telemedicine-based caregiving process for stroke patients to enhance the ambulance design for supporting telemedicine-based care. Seat size, arrangement of assessment equipment, location of telemedicine equipment (computer workstation), and design of telemedicine camera were among the factors that impacted telemedicine-related disruptions. The left ambulance seat zone and head of the patient bed were more involved in environmental hazard–related disruptions, while the right zone of the ambulance was more prone to interruptions and communication-related disruptions.

Discussion

The objectives of this project were to develop a detailed understanding of the task structure and flow for completing a stroke assessment in a telemedicine integrated ambulance, determine the usability issues of the REACH telemedicine system interface and possible human errors that could occur when using this system, and suggest remediations for usability issues and human errors. The first objective was met using observational data to perform an HTA outlining the goals, subgoals, steps, and workflow for each caregiver role. The heuristic evaluation and SHERPA met the second objective, the former by identifying 129 usability violations and the latter by detailing the possible human error occurrences for each observed task. Both heuristic evaluation and SHERPA suggested remediations to improve usability and safe performance, addressing the third objective. While there have been HTAs, heuristic evaluations and usability assessments conducted on telemedicine systems[24–27], studies of human error in stroke care[28–32], and limited study of human error using telemedicine[33], there is little human-centered research on the errors made using telemedicine for stroke care and none using SHERPA to evaluate human error. This study addresses this need by providing a detailed analysis of the types, consequences, probability, criticality, and remediations of human error in a telemedicine system for stroke care.

Results of the heuristic evaluation revealed many violations of common design heuristics. Most prominently the Visibility of System Status, Consistency and Standards, and Error Prevention heuristic violations identified issues with error messages, the layout of the tab structure, data input formats, information architecture, and overall page formatting. Information architecture and the design of the tabs for navigating the system are both important for building a solid foundation for finding information and allowing users to move through the interface. Information architecture involves different models depending on the use of the system; an application focused on fixed steps, for instance, would have a different information architecture from one for browsing. Creating a structure that assists users and is consistent and easy to learn is important in the development of an information architecture. This architecture can also be supported by page formatting, consistency in type face and the use of bold in headings, and an effective organization guiding a user through the system and making items on a page easy to find. Not only should the structure be easy to identify and follow, it should also be easy to access, meaning it should not require additional effort to determine the state of the system and how to navigate it; this is consistent with previous usability findings.[34] Other usability studies have also found similar issues with data input formatting as we found here; with open-ended data input or a nonrestricted format, users often ignore formatting, leading to errors in the system.[35,36] The system studied here also exhibited a lack of error messages or a lack of specificity in the error messages. Error messages are critical feedback for the user, allowing them to move forward in a system and correct future behavior. These messages should be informative, identifying the location of the error and how to fix it, and succinct so that the correction is easy to understand and implement quickly.[37]

The lower number of heuristic violations found for the paramedic role was due to the limited number of interface interactions for that role. The paramedic has only two goals, to log on and select the correct patient case, compared to the nurse and neurologist, each of whom has four goals. The reason for the fewer interactions with the interface is that paramedics are focused solely on patient care. In many cases, the EMT completes the REACH setup before the patient is in the ambulance so that the paramedics only need to interact with the other caregivers via the two-way audio connection in the telemedicine system. They cannot input demographic information or vitals while attending to the patient, meaning the protocol dictates that they communicate this information verbally. This impacts the possibility for human error in this process as the noise level in the ambulance can be high with road noise and sirens and the audio connection through the telemedicine can be impaired because of poor data connections as the ambulance drives through rural areas.

The higher number of usability violations found for the nurse compared to the neurologist can be explained by the amount of free data entry required in this role. Nurses are required to enter dates, names, and vital signs during their tasks, none of which have formatting suggestions in the system, violating heuristics such as Visibility of System Status, Consistency and Standards, and Recognition Rather than Recall. In comparison, although the neurologist role includes data input, the majority is limited to checking boxes and radio buttons to record the patient history, current medications, or allergies or using the drop-down menus selections in the NIHSS. Even though boxes, radio buttons, and drop-down menus are rigid forms of data input which can be restrictive when extra detail is needed, they prevent confusion and errors.

Findings from the SHERPA included the common possible human errors in the telemedicine system for stroke assessment, most of which were information communication or action errors, specifically, miscommunicated, misheard, or unheard communications and incorrect formatting or selection of data input. Communication errors in this system can be caused by unheard or unclear audio, which then requires the communications to be repeated. More common with complex communications through computer systems is misunderstood communication, in which the messenger does not provide adequate information or the receiver does not comprehend the message communicated.[38,39] Data input formatting issues were also a concern found in the heuristic evaluation of this system, with incorrect date formats or misunderstood data input labels with a lack of formatting being were some of the issues seen from the SHERPA. While these errors may seem minor, missing or incorrect data can negatively impact patient care.[40,41] Other healthcare informatics research finding high error and data input has concluded that drop-down selection reduces input errors.[42] These simple changes to the formatting to allow for restricted input can reduce human error in data input.

The consequences for most of the tasks in this process were that the information would not be documented correctly or that a full assessment of the patient could not be formed. While these may not be as severe as causing patient harm, given that tPA is not administered until a CT scan can be conducted, the further consequences of incomplete patient documentation could lead to incomplete links to the EHRs, difficulty connecting to a neurologist, or an incorrect NIHSS, all of which could affect the nurses' and ED physicians' care plan in the hospital or the search strategies of the neurologist when searching the CT imaging for the clots or bleeds that potentially caused the stroke.

Almost all errors could be recovered immediately as the system allows for free data entry after creating the patient case. After the case is created, updating demographics requires entering a sub menu, which is necessary later in the process, meaning that some created patient tasks have a recovery mechanism under the update demographics goal. Other vital sign documentation tasks have recovery steps when the neurologist completes an overview of the patient history. These are advantages in the system, as free data manipulation in the system gives users the chance to correct mistakes and update information to its most current state.

Due to the ambulance telemedicine setup, the neurologist, nurse, and paramedic could see the patient either directly or virtually through video feeds. However, the patient could see only the paramedic in the ambulance and communicated verbally with the neurologist, often following prompts from the paramedic. The neurologist also had an incomplete view of the patients and could not easily see if they followed the prompts. This situation resulted in the neurologist asking the paramedic to perform tasks such as facial evaluation and to report the results. Given that the patient–neurologist pair contributed to 35% of the interactions observed and the provision of safe and effective care depends on good communication between the patient and neurologist, it is imperative that the telemedicine setup in the ambulance be designed to provide good visual and auditory connections between these two team members.

Whereas verbal communication plays an important role in obtaining and updating patient information, nonverbal communication was used frequently during patient stroke care evaluation tasks such as the evaluation of sensation, arm and leg movement, and visual field. This communication involved the patients responding to prompts from the paramedic or neurologist to move body parts or indicate how they were feeling. However, it was often difficult for the neurologist to evaluate the patient's condition due to the incomplete field of view resulting from the positioning of the cameras, requiring the paramedic to serve as intermediator. Tasks related to updating patient information, which involved frequent verbal exchanges, were disrupted as often as those related to evaluating sensation where nonverbal means were also used. Investigating the nature of communication and teamwork in telemedicine is challenging because the care team is geographically distributed and capturing team interactions simultaneously is difficult from a research perspective. This study was able to collect parallel video data at three locations and merge the video feeds such that they could be viewed and coded simultaneously to understand how team members dynamically interact with one another to coordinate information and make decisions in the care context. This coordination is particularly important in a constrained setting like an ambulance where in-person observation is difficult. This approach could be adapted and used in future studies of team behavior in telemedicine-enabled care. Studying team interactions in the context of critical stroke care evaluation tasks allowed us to understand how team members communicated to build the shared mental models needed to perform their tasks. Understanding the structure and nature of team interactions in this context is critical for identifying interventions that support successful implementation of telemedicine-enabled stroke care.

Remediations and Design Implications.

This project revealed that the current approach to integrating the telemedicine system in the ambulance along with its design created disruptions during the stroke caregiving process. Remediations developed based on heuristic evaluation and SHERPA findings are organized below by work system category from the SEIPS 2.0 model.[9]

Tools and Technology

Highlighting and labelling. Consistent use of color, bolding and labelling formats should be used in the design of the system not only to create a cohesive aesthetic but also to provide a sense of hierarchy and organization. Data labels for all input should be located close to the input boxes and be clear, concise and consistent. This not only allows the users to identify quickly and correctly where the data should be recorded but also is aesthetically pleasing on an interface. In terms of the SEIPS 2.0 model, changing the labelling and use of color on the interface impacts the work system through the tools and technology factor, but a clear organization can also impact how caregivers complete the task. The use of color, bolding, and size can provide a subtle structure to data input tasks and impact how users complete tasks or organize their work. This, in turn, can make users more efficient by making the organization of the system transparent.

Error messages. A common violation described in the heuristic evaluation involved data input tasks with requirements that have to be met before the user can log on, create a patient case or move through the system. Frequently there was little to no information about which items were the issue or how to fix those items. Providing salient error messages that help the user to recover is crucial to the usability of a system. Error messages should follow design standards and include the item that needs to be changed, the severity of the error and suggestions for how to fix it. As this change affects only the interface of the telemedicine design, it impacts only the tools and technology factor. However, as the SEIPS 2.0 model describes changes to the tools and technology in the interface impact the task, internal environment, organization, external environment, and person factors in the work system.

Layout. The organization of the data input screens in this telemedicine system were the consistent source of usability violations in the neurologist's role. This role is the only one that consistently uses the tab structure in the REACH system to complete their tasks. Many evaluators reported that the visual design of the tabs did not make it clear that they were able to click on them to access different data inputs. This issue violated the Consistency and Standards, Flexibility and Efficiency of Use, Visibility of System Status, and Error Prevention heuristics. Each item in an interface should have a clear purpose, and communicating that purpose through design is crucial to usability. This is typically done though platform conventions. Evaluators also mentioned that the organization of the tabs and subtabs made moving through the system confusing as there were multiple scrolling sections in the display, violating the Flexibility and Efficiency of Use heuristic. A simpler design of tabs organized by the task flow of the user would improve user experience and efficiency as organization prevents extraneous movement in the system. Similar to the labelling remediation, these changes in layout affect the SEIPS model work system through the tools and technology factor and the task factor because of the impact on the task organization mentioned previously.

Formatting. Given the large amount of data entered into this system, many task remediations focused on changes to the telemedicine system such that the data required to be entered in the process is clear by highlighting areas for data input. Another remediation suggested was rigid or suggested formatting. For data input such as dates and times, rigid formatting was suggested, meaning segmenting the data input such that the data are entered in a format consistently (for example separate data inputs for month, date and year), could eliminate confusion and maintain consistency in data input. This change reduces the number of errors involving switching day and month or entering month as an abbreviated word rather than a number. Suggested formatting could be used for such data as patient blood pressure, heart rate, or blood oxygenation by providing an example of a typical input with the correct units. For example, near the blood pressure data input, a text label could identify “132/88 mmHg” as an example of blood pressure formatting. This works well to mediate errors and address heuristic violations. Consistent and rigid formatting supports recognition rather than recall and helps users prevent errors and recover from them quickly as the formatting should make mistakes obvious. Again, this remediation focuses on the design of the interface and as such directly impacts the tools and technology work system factor in the SEIPS 2.0 model.

Tasks

Automation. For tasks that require manipulation of controls, such as the camera focused on the patient, automation could be implemented. A simple command or control would focus the camera on an area of the patient rather than requiring the neurologist to manually control the camera by clicking directional and zoom arrows. For assessment items that require a close view of the patient’s facial movements, a control could allow the camera to detect the patient’s face and zoom in, or for items requiring visuals of leg movements, the camera could move to the lower portion of the patient. Additionally, this functionality could be automated such that as assessment items are completed, the view the neurologist needs for the next item would be implemented as the previous assessment item was completed. Automating the movement within this system with set view controls could eliminate over or under correction of the camera location and reduce the instances that an assessment item is incorrectly recorded due to lack of detailed visibility. Further automating to set the views as neurologists work through assessment items would allow for a consistent assessment order for the neurologist and paramedics and simplify the movements needed to complete the task. Implementation of automation would impact the tools and technology work system factor, and automation based on tasks step would impact the task work system factor. The task change may also impact the communication in the system as a standardized task flow would limit the need for the neurologist to communicate the assessment needed, thus impacting the person work system factor.

Infernal Environnent

Audio/Vidéo Improvement. There are many communication tasks in this system that could be impacted by poor quality data connections or audio equipment. Not being able to hear or understand from either the neurologist or paramedic perspective requires multiple repetitions of information or physical movement in the ambulance to view the neurologist. Improvements to the equipment in the ambulance could eliminate or reduce the instances of miscommunications or work arounds. Improved microphones and speakers could make the audio connection clearer for both the neurologist and paramedic, reducing the need for repeated communications. Easily accessible views of the neurologist from the patient's side would allow the paramedic to make use of nonverbal communication with them. Based on the RTA protocol applied in this study, many neurologists mentioned that they would mime movements they wanted paramedics to use in the assessment whether they could be seen or not.

Often the paramedics leave the laptop connected to the REACH program in the front of the ambulance as it is the most stable place for it and movement is restricted by the wired connections to the laptop. Many paramedics mentioned their frustration that when instruction is needed from the neurologist, they must leave the patient's bedside to access the laptop. A screen at the rear of the ambulance so that patient care tasks are not interrupted would be ideal for providing a visual of the neurologist for that visual communication. In addition, closed captioning on a visible screen for the paramedics and neurologists could possibly provide some support in understanding audio degraded by poor data connections. These improvements primarily impact the tools and technology work system factor. However, the implementation of these tools affects the physical layout of the ambulance; thus, the internal environment work system factor is impacted as well. In addition, the support of communication and use of the system without moving from the patient's bedside could impact the task factor, decreasing the effort or repetition of communication needed to complete the assessment items.

Organization

Training. Consistency in procedure steps and increased familiarity with the assessment steps are the training remediations suggested by this analysis. Specifically based on the NIHSS errors in communication, unheard or misheard assessment steps and under communicated instructions for physical assessment could be reduced with training for paramedics on the tasks they need to assist with and knowing the order in which to expect those assessment tasks. This could reduce the instances of repeated communication from the neurologist and, thus, the probability of miscommunication. In particular, training in the movements needed for the assessment as well as their correct application could eliminate the need for the neurologist to communicate techniques that are often either unheard or misunderstood. This remediation focuses on the changes to the organization work system factor, but this training could impact the person factor by providing knowledge about the assessment and the task factor by changing the sequence and reducing the difficulty of the assessment task.

Error remediation techniques suggested in this analysis primarily focus on interface system improvements rather than the use of training or environmental changes. This is due to the constraints of the physical environment in ambulances, meaning additional equipment would need to be carefully considered for necessity and placement, and the mobile and complex nature of the nursing stations makes it difficult to implement lasting environmental changes. In addition, all caregivers in this process have rigorous training that they complete for many aspects of their jobs, meaning additional training for this single process should be kept to a minimum.

Many remediations were developed so that the process of completing the assessment is consistent, correct, and as quick as possible. To do this, the main problems of data collection and data input needed to be assessed. Supporting the communications of the paramedic and the neurologist through the telemedicine system is the primary remediation for errors of information communication. Setting a protocol and order for data collection can create redundancy in the communications. The remediation from the NIHSS assessment requiring training of neurologists to complete the assessment in a specific order for each patient would allow for consistent evaluation and better prediction of commands for the paramedic or nurse. This remediation is two-fold: it prevents lost or incomplete assessment items by following a checklist and making use of retrieval cues, thus improving performance, and it eliminates the need for redundant communication and alleviates dependence on audio connection as all members of the team would be able to predict the next item to be assessed. Most of the other remediations focus on formatting suggestions, which allow for consistency and provide an error check for users before they enter the data.

Based on the findings from this project and the previous work conducted by the team, the following recommendations and guidance are provided for retrofitting existing ambulances or designing new ambulances for telemedicine-based stroke care.

- Distribute evaluation equipment alongside the larger ambulance seat and provide better ergonomic access for the paramedic to access the evaluation equipment without twisting or turning.
- Provide visual access to the telemedicine laptop/monitor from the left/right seat zone and from the paramedic workstation. The visual access to the laptop/monitor might be possible if this monitor is integrated in the ambulance design in the proximity of the microphone/speaker and by enhancing the monitor with a flexible/rotating stand.
- Provide a wider lens camera or flexible/rotating design for the camera to cover and record the existing blind spots near the ambulance door and patient legs such that the neurologist can conduct the evaluation more effectively with reduced input from the paramedic.
- Provide a monitor to enable the patient to directly see the remotely located neurologist to facilitate more effective communication between patient and neurologist.
- Integrate a soundproof design for the ambulance exterior panels to eliminate exterior noise and siren noise so that the paramedic can communicate through the microphone/speaker more efficiently.

Conclusion

Completing a stroke assessment in an ambulance using telemedicine is a complex process that is prone to error, as in all processes both simple and complex. Many issues were found in the interface, revealing problems with the system’s design concerning information architecture, error messages, and page formatting. Predicted errors included miscommunication, omitted or incomplete steps, incorrect data entry, and insufficient assessment. The consequences were discussed with limited probability of patient harm, but some with implications to the patient care process beyond the ambulance. Finally, remediations were suggested for the disruptions to process flow and usability issues. These remediations will be considered as the research team further investigates the use of this telemedicine system for prehospital stroke assessment and suggestions for system improvement.

6. LIST OF PUBLICATIONS AND PRODUCTS

The list of *four* journal publications and *six* conference presentations resulting from this effort are provided below.

Journal Publications:

1. Comparing sources of disruptions to telemedicine-enabled stroke care in an ambulance.[43] Published in the journal *HERD: Health Environments Research & Design Journal.*
2. An exploratory study investigating the barriers, facilitators, and demands affecting caregivers in a telemedicine integrated ambulance-based setting for stroke care.[23] Published in the journal *Applied Ergonomics.*
3. Communication and teamwork during telemedicine-enabled stroke care in an ambulance.[44] Published in the journal *Human Factors.*
4. Task, usability, and error analyses of ambulance-based telemedicine for stroke care.[22] Published in the journal *IISE Transactions on Healthcare Systems Engineering.*

Conference papers:

1. Rogers, H., Ponathil, A., Chalil Madathil, K., Joseph, A., McNeese, N., Holmstedt, C., & McElligott, J. (2020, December). Evaluation and prediction of human error in ambulance-based telemedicine stroke assessment. In *Proceedings of the human factors and ergonomics society annual meeting. Los Angeles*. [45]
2. Mihandoust, S., Joseph, A., Chalil Madathil, K., Jafarifiroozabadi, R., & Rogers, H. (2021, May). Understanding sources of disruptions to telemedicine-based stroke care in an ambulance using simulation. In *Proceedings of the 2021 Environmental Design Research Association (EDRA 52)* Conference, Detroit, MI, United States.[46]
3. Rogers, H., Chalil Madathil, K., Joseph, A., Holmstedt, C., Qanungo, S., McNeese, N., Morris, T., Holden, R. & McElligott, J. (2021, May). Barriers and facilitators in a telemedicine-integrated ambulance-based setting for stroke care. In *Proceedings of the 2021 IEA Conference*.[47]
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5. Rogers, H., Joseph, A., Chalil Madathil, K., McNeese, N., Ponathil, A., Holmstedt, C., & McElligott, J. (2020, May 18-21). Heuristic Evaluation of a Pilot Telemedicine System for Stroke Evaluation in Ambulances. Presented at the *2020 International Symposium on Human Factors and Ergonomics in Health Care*.[49]
6. Rogers, H., Chalil Madathil, K., Joseph, A., Holmstedt, C. & McElligott, J. (2020, March). Workflow barriers in a telemedicine-integrated ambulance-based setting for stroke care. Accepted for presentation at the *2020 Harriet and Jerry Dempsey Research Conference*, Greenville, SC. [Conference was cancelled due to COVID-19 pandemic].

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