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An Integrated Cognitive Performance Evaluation Framework for Urban Search and Rescue Applications

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***Abstract*—**A variety of techniques and methods are available to evaluate cognitive performance in Urban Search and Rescue (USAR) applications. However, traditional cognitive performance evaluation techniques typically incorporate either the conscious or systematic aspect, failing to take into consideration the subconscious or intuitive aspect. This leads to incomplete measures and produces ineffective designs. In order to fill the gaps in past research, this study developed a theoretical framework to facilitate the integration of situation awareness (SA) and intuitive pattern recognition (IPR) to enhance the cognitive performance representation in USAR applications. This framework provides guidance to integrate both SA and IPR in order to evaluate the cognitive performance of the USAR responders. The application of this framework will help improve the system design.

***Keywords*—**Cognitive performance, intuitive pattern recognition, situation awareness, urban search and rescue.

I. Introduction

URBAN Search and Rescue (USAR) consists of responders who work to stabilize damaged structures, locate and extricate victims, identify risks of additional collapses, and provide medical treatment to victims. USAR environments are highly complex, and can sometimes be too dangerous to deploy USAR responders to locate and assist victims due to structural hazards that have the potential for secondary collapses, hidden hazards such as the disbursement of toxic gases, and personal hazards such as getting lost inside a building or extreme exhaustion [1]. The utilization of rescue robots can avoid placing USAR responders in harm's way while still being able to analyze the situation and relay feedback to the USAR responder. Over time, continuous advancements in this technology have permitted the use of highly autonomous rescue robots shifting the responder's initial duties from a more physical presence to a more mentally based position. Therefore, it is important to address the effectiveness of the system that measures the responder's cognitive performance. Existing cognitive performance evaluation methods range from qualitative questionnaires and interviews to quantitative biomechanical measurement tools. However, these methods only incorporate the conscious or systematic aspect of performance (the situational awareness component), and fail to integrate the subconscious or intuitive aspect to account for the ideas and conceptualization of the total responder's decision-making experience [2]. Situation awareness (SA) is a valuable and frequently used component when assessing cognitive performance in complex environments. However, assessing the situation awareness component only accommodates the conscious or systematic piece of the USAR responder's decision-making ability failing to recognize the subconscious component, which plays an important role in how they make decisions in complex environments such as USAR. Neglecting the intuitive aspect when assessing cognitive performance can lead to insufficient development of interface designs, which can have serious consequences. Therefore, research needs more effort devoted towards incorporating both conscious and subconscious aspects of cognitive performance in interface designs. This study proposes an integrated framework to evaluate the responder cognitive performance. In an attempt to understand relationships and their contribution to evaluating the effectiveness of the interface design, the framework provides a way to account for the responder's comprehensive decision-making performance. In order to study responder's cognitive performance within the domain of USAR, the study uses concepts from theoretical frameworks such as rapid prototyping technique, Accumulated Clues Task (ACT), and Quantitative Analysis of Situational Awareness (QUASA).

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II. Integrated Framework

A framework that integrates situational awareness and intuitive pattern recognition (IPR) to enhance the cognitive performance representation in USAR was developed. The integrated framework consists of a sequence of procedures that can be used as a blueprint in the identification of the USAR responder's total cognitive performance to both investigate and improve the system design.

As can be seen in Fig. 1, the integrated framework consists of six steps: (1) constructing a cognitive task analysis to understand the cognitive tasks in USAR domain, (2) identifying knowledge associated with a particular task and utilizing the developed SA and IPR design requirements to form SA and IPR goals and scenarios; (3) developing a SA and IPR design to execute an assessment for all cognitive components; (4) collecting cognitive performance data; (5) an approach to evaluate findings quantitatively; and 6) drawing conclusions.

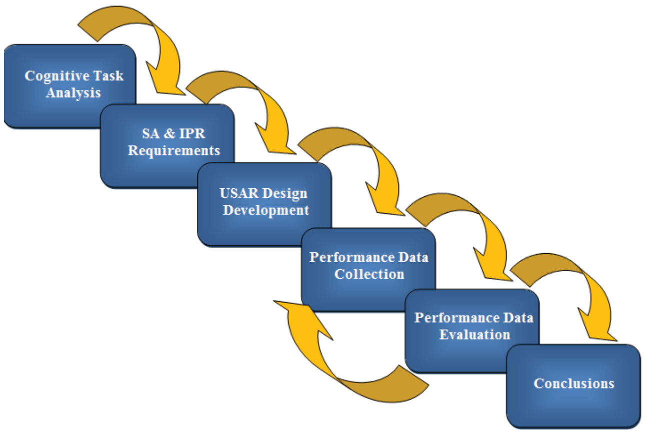

Fig. 1 Integrated cognitive performance framework for USAR application

A. Cognitive Task Analysis

One of the most important issues that this framework should necessarily address is accurately defining responders' cognitive tasks in the USAR domain. In a USAR domain, cognitive tasks are usually complex in nature and defined as those where performance requires an integrated use of both controlled (conscious, conceptual) and automated (unconscious, procedural or strategic) knowledge to perform those cognitive tasks [3]. Therefore, a cognitive task analysis should be used as it captures a description of the knowledge that USAR responders use to perform these complex tasks. A cognitive task analysis (CTA) is often one of the strategies used to describe the knowledge required for cognitive performance [4]. Cognitive task analysis (CTA) uses a variety of interview and observation strategies to capture accurate and complete descriptions of cognitive processes and decisions. The purpose of a cognitive task analysis is to define the decision requirements systematically and psychological processes used by expert individuals (i.e., performers) in accomplishing results [5].

To develop the cognitive tasks analysis for USAR, a combination of procedures should be followed to identify those tasks that merit detailed study [6].

The initial step includes developing a general understanding of the USAR domain in which the cognitive task analysis will be conducted, and developing a sense of vocabulary associated with the USAR domain. Next, two or more USAR Subject Matter Experts (SMEs) should be recruited as they display in-depth knowledge of the domain requirements in USAR environments. To be considered as reliable candidates, SMEs should have recent experience in both teaching and performing cognitive skills in USAR situations. After recruiting SMEs, information associated with USAR related tasks should be identified and structured. A series of potential sub-steps are suggested, which include: Documented literature review and analysis; Observation; Structured and/or Unstructured interviews; and Concurrent verbal protocol analysis.

- **Documented literature review and analysis:** Review literature that provides relevant information on the tasks identified. Include documents such as, job descriptions, reports, training materials etc. Reviewing this information enhances interviews with experts, and provides the ability to dispute discrepancies between training/performance.
- **Observation:** Observe experts conducting the task and procedures of interest to the cognitive tasks analysis. Record the actions that are naturally part of the process of executing the tasks of interest. At the same time, focus on the completion process which include experts engaging in decision making, analysis and other critical cognitive tasks.
- **Structured and/or Unstructured interviews:** For these interviews, the goal is to ask the USAR expert direct questions that will provide additional information about the USAR domain. One approach could be to ask the USAR expert (a) to list all the steps involved in completing the subtasks that are part of the larger task being studied (b) to identify the key decision points, and when those decision points appear, (c) possible procedures that can be used to make decisions between alternate options, (d) the conceptual knowledge needed to tackle the subtasks, and (e) how the expert determines when the conditions call for beginning the process for doing the subtasks(s).
- **Concurrent verbal protocol analysis:** To begin protocol analysis, work with experts to identify a good representative task in the task area. Develop a problem/scenario around the representative task, and ask several experts to review and modify the problem/scenario before using it for knowledge elicitation. Prepare and train the expert for solving problems aloud by giving him/her instructions on how to think aloud. Next, present the main problem/challenge to the expert. Record all of the verbal utterances of the expert as he/she solves the problem [6].

A variety of cognitive task analysis methods is available with the capabilities of applying these cognitive procedures. However, since each method has its own approach in identifying cognitive performance tasks, goals, and processes, caution must be taken prior to method selection. Table I identifies examples of possible cognitive task analysis methods appropriate but not limited to representing cognitive performance in USAR. The most frequently utilized cognitive task analysis method is the goal-directed task analysis (GDTA) [7]. GDTA allows the primary goals of the mission to be identified, along with the sub goals necessary for meeting each primary goal. Associated with each sub goal, the major decisions facing the responder are identified. Ultimately, the cognitive task analysis should provide an overall understanding of the cognitive tasks associated with USAR and the associated goals and requirements for making decisions. This information should then be used when narrowing the scope of the cognitive tasks and goals specific to a particular USAR scenario.

B. SA and IPA Requirements

Due to the fact that there will be a multitude of information initially collected from the GDTA, a knowledge audit should be performed with USAR SMEs. The knowledge audit identifies ways in which expertise is used in a USAR domain. This approach captures the most important aspects of expertise in USAR and provides a means to identify specific tasks deemed important.

TABLE I
EXAMPLES OF COGNITIVE TASK ANALYSIS METHODS

CTA Methods	Description
Applied Cognitive Task Analysis (APTA)	Models cognitive performance using three consecutive structured interviews to elicit insight into the cognitive processes used by the expert in the scenario context [8].
Critical Decision Method (CDM)	Process involving an analyst working with an expert in an attempt to identify key points for an incident where which he/she had to apply his/her expertise to a critical and uncommon situation that relates to the task area of interest and when decisions had to be made in the incident [9].
Cognitive Oriented Task Analysis (COTA)	Procedures flexibly applied to describing the expertise that supports overall job performance [4].
Decompose, Network, and Assess Method (DNA)	Provides an easy procedure to elicit knowledge and skills elements from experts and represent the diverse kinds of knowledge required to reason and function in any domain [10].
Goal Directed Task Analysis (GDTA)	Process in which the major goals of a particular job class are identified along with the major sub goals necessary for meeting each of these goals [10].

A set of questions should be designed to elicit descriptions of specific types of USAR domain knowledge, skill, and appropriate examples. The goal is to find out the nature of these skills, specific events where they were required, and resources that have been used. The list below demonstrates the series of questions (as seen in Table II) that could be used to assure these parameters are met:

TABLE II
EXAMPLES OF QUESTIONS

Description
Question1 Can you give me an example of an environmental scenario you considered extremely dangerous for USAR responders?
Question 2 Can you give me example events that required the use of a technical search and rescue robot?
Question 3 What tasks did you feel to be the most suitable for this scenario?
Question 4 What situation awareness related goals did you expect to be associated with this scenario?
Question 5 What intuitive response related goals did you expect to be associated with this scenario?
Question 6 What major elements were you looking for when understanding the situation?
Question 7 What major elements were you looking for when determining the type of situation?

Specific events will be identified from the information collected. For each event, collection of the USAR SMEs mental simulation of the most plausible course of action will be documented. From the mental simulation, the collection of related goals, situation awareness and intuitive pattern recognition in relation to the USAR events identified will also be documented. A comprehensive list of the most plausible goals associated with the specific events identified will be generated after reviewing and comparing the goals. Cues perceived to assist in understanding the situation awareness related goals and establishing intuitive pattern recognition related goals will also be documented.

The goals should focus not only on what general information the USAR responder needs, but also the style in which the cue information should align with the goals, and how the goal information should align with the design of the system. For this reason, a series of requirements are developed to guide the design of the statements used to measure SA and IPR related goals. A series of twenty design requirements were developed for this framework to establish the form for presenting SA and IPR statements for a particular USAR event. These requirements promote consistency when addressing situation awareness (SA) goals and intuitive pattern recognition (IPR) goals specific to USAR applications. The design requirements were separated into four categories consisting of general information requirements, goal requirements, cue requirements, and system design requirements. These categories address the requirement needs specific to SA requirements needs, IPR requirements needs, and both SA and IPR requirements needs. The guidelines illustrated in Table III outline the constraints of requirements for the type of general information that should be included in the USAR event. These guidelines give insight on displaying additional information when highlighting the goal for the USAR event. If potential goals demonstrated by an USAR event do not comply with general information guidelines, remove or alter those USAR events to fit the guidelines.

TABLE III
SUMMARY OF GENERAL DESIGN GUIDELINES FOR USAR DOMAINS

SA and IPR Requirements	SA	IPR	Both
Information should be provided that maintains the USAR theme			✓
Information should be presented clearly; in a fashion consistent with USAR expectations			✓
Present information that support a mixture of USAR situations/scenarios			✓
Information should be provided that support the state of the USAR situation/scenario	✓		
Information should be provided that maintains the USAR theme			✓
Information should be provided that support an intuitive response regarding the type of a USAR situation/scenario		✓	
Unrealistic information should be removed from the USAR environment; pending it doesn't conflict with SA and IPR			✓

The guidelines illustrated in Table IV outline the constraints of the requirements according to the manner in which the statements should be presented in the USAR events. These guidelines highlight areas such as the type of information the statements should provide and the format in which the goal should comply. In the event these guidelines are unmet, eliminate or alter the potential goal to fit the criteria.

The guidelines illustrated in Table V address the constraints of the requirements in regards to the type of cue information provided in association with the goals of the USAR events and demonstrate that the cues provided must satisfy limitations such as addressing the USAR theme at all times and the ability to be easily identified in the USAR event.

TABLE IV
SUMMARY OF DESIGN GUIDELINES FOR USAR STATEMENTS

SA and IPR Requirements	SA	IPR	Both
Statements should not focus on decisions for the USAR situation/scenario			✓
Statements for the USAR situation/scenario must be in a structure easy to respond to			✓
Statements for the USAR situation/scenario must have a right or wrong answer			✓
Statements should support typical USAR responder's response for the type of USAR situation/scenario provided		✓	
Statements should represent UASR responder's understanding of the USAR situation	✓		
Present a variety of statements that encourage a response for the type of USAR situation/scenario presented; Statements should not focus on one or two responses		✓	

TABLE V
SUMMARY OF DESIGN GUIDELINES FOR CUES IN USAR DOMAIN

SA and IPR Requirements	SA	IPR	Both
Cues presented should support USAR theme at any point			✓
Cues presented should be easy to identify in the USAR environment			✓
Cues should be provided in a logical and consistent order according to USAR protocol		✓	
Cues presented should support USAR theme at any point			✓

Violations of any of the guidelines should result in eliminating or altering the associated goals to fit the criteria. The guidelines demonstrated in Table VI addresses the constraints of the requirements with regard to design guidelines for cues and the system in the USAR domain. This component illustrates the manner in which the SA and IPR design should present the information. If the goals of the USAR event do not align with how the system presents the information, eliminate or alter the goals to fit the criteria.

TABLE VI
SUMMARY OF DESIGN GUIDELINES FOR SYSTEMS IN USAR DOMAIN

SA and IPR Requirements	SA	IPR	Both
Dynamic representation of the entire USAR landscape should be displayed		✓	
Use automation for assistance in carrying out consistent actions rather than higher level cognitive tasks			✓
Physical tasks for the USAR responder should be minimized			✓

From these guidelines, USAR events should be developed that comply with the requirements for situation awareness goals, and intuitive pattern recognition goals; associated cues should be determined; and goals should be aligned with consistent system design set up.

C. USAR Design Development

Ideally, these USAR events should be applied to real world situations. However, because USAR environments are categorized as dynamic in nature, unpredictable in occurrence, and pose safety risks, testing subjects in the actual environment is often viewed as unfeasible to accomplish. Therefore, an alternative is the use of simulation. Such technology allows computer-based simulated scenarios to be constructed that emulate the behavior of the prototype system and environment allowing the assessment of cognitive processes performed by the USAR responder.

For this framework, a computer based simulation program should be utilized that provide the opportunity to create and manipulate the complex nature of a realistic USAR environment, to follow the laws of physics, to develop simulated USAR scenarios, and to safely collect data in regards to the responders' cognitive tasks performed. The simulation software must also have the ability to integrate cognitive performance queries into USAR simulated scenario, develop and embed interface designs into the USAR simulated environment, and add various elements most notably rescue robots to provide the ability to maneuver throughout the simulated environment. Since, a number of simulations can cause much difficulty in describing and re-creating these complex environments; when selecting simulation software it is important that its functionality meet the criteria. Therefore, simulation functionalities must be compared to assure these framework needs are met. Table VII gives a checklist that identifies the mandatory requirements in which the computer-based simulation must possess to be acceptable for this framework.

TABLE VII
COMPUTER BASED SIMULATION REQUIREMENTS CHECKLIST

3-D Simulation Type	☐
High Level Documentation	☐
Sensors	☐
Graphical User Interface Design	☐

For the Simulator Type, it describes that the software should provide 3-D simulation environments to mimic real world features. High Level Documentation states the documentation should provide descriptions of the functions in the software. Sensors, defines that sensors should be available to provide feedback to the USAR responder concerning the state of the environment and objects encountered. Graphical user interface verifies that a user interface should be available to provide a visual representation of objects and provides functional human robotic interaction.

There is a variety of simulation software available that have the potential to meet the capabilities required for the USAR scenario recreation. However, because research in the urban search and rescue (USAR) field has experienced the most vigorous development in recent years within the robotics community, many of the USAR tasks focus on robotic behaviors and the development of robotics simulation software to represent USAR scenarios [11].

One of the most effective and user-friendly robotic simulation software is Microsoft Robotics Developer Studio (MRDS). MRDS is a window-based environment used for robot control and simulation [12]. MRDS is a development platform in the robotics community that supports a wide variety of users, hardware, and application scenarios. MRDS is an integrated programming environment making it possible to debug robotics applications without having to make any assumptions about the underlying hardware [12] that includes such tools as Microsoft Visual C Sharp (C#) projects, Microsoft Visual Programming Language (VPL), 3D Visual Simulation Environment (VSE), and the newly added Simple Programming Language (SPL).

The robotic simulation software should provide a development platform that supports the creation of USAR scenarios. Distinctive simulated components should be developed to assist in the assessment of USAR responder's cognitive performance with regard to situation awareness, intuitive pattern recognition. In the end, it is important that the simulation provide the ability to create the appropriate components in a format consist with the requirements.

D. Performance Data Collection

Using this framework, objective measures of SA and IPR are developed to investigate total cognitive performance for the USAR scenarios. Cognitive workload also is measured as a comparison analysis between cognitive effort and cognitive performance. Therefore, to collect data from the functional interface design(s) and validate the USAR environments, a number of computer based probes and computerized post-task participant questionnaire are developed.

Using the simulation software, computer based probe designs for the USAR is constructed to collect the cognitive performance of the responder in regards to SA and IPR. The computer-based probes provide the ability to display the query information in regards to SA statements and IPR statements, collected. Then, the probes are programmed to be answered at discrete decision points throughout the simulated scenarios. The answered SA component yields output in the form of the responder's situational understanding based on the percentage of correct situations identified. In addition, the IPR component yields output in the form of the responder's intuitive response displayed by the percentage of correct situational responses recognized.

In addition to using simulation software, a computerized post task questionnaire (for the USAR domain) is constructed to collect cognitive workload data from the responders. The computerized post task questionnaire provides the ability to display USAR related statements that measure cognitive workload usually across six dimensions, namely, effort, mental demand, performance, frustration, and physical demand. These items then are rated on a 0-100 percent scale. Where a rating of 0 means the USAR responder was not working hard to understand and react to that situation, and 100 means the USAR responder was working extremely hard to understand and react to that situation. In addition to collecting SA and IPR scores, it is vital to define an appropriate representation of the impact of each component on the responder's cognitive performance at a sufficient level to allow realistic cognitive performance values to be estimated. Since there is limited research that supports an established quantitative breakdown between situation awareness and intuitive pattern recognition in USAR domains, an alternative approach was developed. For this framework, in order to provide an accurate percentage breakdown, active USAR SMEs are recruited to document their perceived percentage of impact between situational awareness and intuitive pattern recognition in USAR environments. A highly suggested approach in collecting this information is the use structured and/or unstructured interviews as this allows the ability for direct questions about the USAR domain. Then, an averaged percentage is applied to each component to model USAR SA percentage of impact breakdown and IPR percentage of impact breakdown.

E. Performance Data Evaluation

In order to assess the responder's cognitive performance and cognitive workload, the measurements must be quantified to verify different measurement levels. Since the collected measures should convey the key pieces of information specific to the situational awareness percentage scores, intuitive pattern recognition percentage scores, cognitive workload percentage scores, and impact percentage of SA and IPR components, a quantitative approach is needed to integrate and evaluate the total cognitive performance and cognitive workload.

Given that the cognitive tasks within the integrated framework represent percentages of correctly identified situations for situation awareness performance and percentages of correctly recognized responses for intuitive pattern recognition performance, model formulation can be described in terms of the system's ability to match the responder's total cognitive performance. The total cognitive performance of the USAR responders can be described as the summation of the responder's situation awareness (*SAR*) plus the responder's intuitive pattern recognition (*IPRR*). The responder situation awareness (*SAR*) performance is measured by the summation of the cognitive impact percentage breakdown multiplied by the percentage of correctly identified situations. Whereas, the responder intuitive pattern (*IPRR*) recognition performance is measured by the summation of the cognitive impact percentage breakdown multiplied by the percentage of correctly recognized responses. The results from both calculations should then be added together to generate the total cognitive performance of the USAR responder.

The cognitive workload component should be documented as the amount of mental effort required from each USAR participant performing each task. The cognitive workload component is recognized as a post-test performed directly following each task. This method yields output in the form of the percentage of mental workload for each task. In order to obtain percentage scores for these dimensions, a scale of twenty bipolar ratings were developed, a score from 0% - 100% is assigned to each point on the scale to the nearest 5%, and each dimension is assigned an individual scale. Next, in an effort to prioritize and assign weights based on the significance of the dimension, a paired comparison between the dimensions was performed. Finally, a global workload score was developed across all dimensions. Hence, these dimensions provide insight on the mental workload experienced when performing these complex tasks.

F. Drawing Conclusion

Having the cognitive components accounted for and integrated in the framework provides the ability to assess the USAR participant's total cognitive performance accurately. Throughout the human factors community, a significant amount of research correlates cognitive improvement with positive cognitive performance. Research also supports the idea that there is an inverse relationship between cognitive performance and the amount of cognitive workload required when performing complex tasks. For example, as cognitive performance increases the cognitive workload would decrease or vice versa [13]. Therefore, the variation between the two components (total cognitive performance and cognitive workload) should be used to determine the cognitive performance of the USAR responder in relation to the amount of mental effort required by the responder when performing cognitive tasks. In ensuring satisfactory results, a comparison of the USAR participants' cognitive performance should be investigated with a focus on the state of the responder's cognitive performance and cognitive workload.

III. Conclusion

When disaster strikes, USAR responder's decision-making process plays a significant role in this highly complex, and often very dangerous environment. A variety of techniques and methods are available to evaluate the responder's cognitive performance. However, traditional cognitive performance evaluation techniques fail to take into consideration the subconscious or intuitive aspect and can lead to incomplete measures and produce ineffective designs which can have serious consequence for USAR missions. This study developed a theoretical framework to facilitate the integration of situational awareness (SA) and intuitive pattern recognition (IPR) to enhance the cognitive performance representation in USAR applications. The purpose of this framework is to provide a common structure for the integration of SA and IPR in USAR domains that take into consideration both conscious and subconscious aspects of cognitive performance.

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