ABSTRACT

GREEN, REBECCA SUE. Cognitive Task Analyses for Life Science Automation Training Program Design. (Under the direction of David Kaber and Christopher Mayhorn.)

The purpose of this study was to develop a systematic approach to the translation of Cognitive Task Analyses (CTAs), including Goal Directed Task Analysis (GDTA) and Abstraction Hierarchy (AH) models, into a Situation Awareness (SA) based training program for operators of High-throughput (biological) screening (HTS) systems. Traditional on-the-job (OTJ) training of new HTS operators usually consists of several weeks of assisting a lead biochemist to become familiar with methods and automated systems. Unfortunately, this approach to training is typically unstructured and learning results may be highly variable. In order to design instruction to support learning of cognitive processes as part of HTS, the information demands engendered by the task need to be identified. This can be achieved using CTAs as the basis for training program design. Various CTA methods, including the Critical Decision Method (CDM) and Precursor-Action-Results-Interpretation, have been used to develop training. However, no standardized methods exist for relating the outcomes of the integration of multiple CTA methods to support training program design.

This study, therefore, combined information requirements from a GDTA and system resource requirements identified through AH models to establish content on HTS processes for delivery through an electronic training program. The goals and sequences of task steps within the training program were identified by the GDTA. The use of AH models of the HTS system provided a method for determining the purpose and function of the software and devices relative to different operator functional requirements. This combination of information from the CTAs provided a systematic approach for specifying training strategies

and parameters. The training program presented learners with content for development of the three levels of operator SA (perception, comprehension, and projection) and knowledge structures pertaining to HTS system operations. Following development of the prototype electronic training program and the comparison traditional training program, an evaluation occurred through a three-part survey with comparison to the traditional lab training provided to expert operators of an HTS system. The evaluation incorporated two knowledge assessment tests, a usability survey, and a survey of the effectiveness of the SA elements of the training program.

Results provided preliminary evidence that a CTA-based training program can improve operators' knowledge structures beyond OTJ training. Furthermore, operator performance on SA questions indicated improvements in knowledge structures associated with perceptual elements, comprehension of those elements, and projection of the future states of HTS systems. Additionally, since experience can lead to differences in operator mental models pertaining to HTS systems, the effect of two types of overall experience and individual task experience were measured. Results indicated that the CTA-based training program was effective in providing improved SA knowledge and general knowledge structures for HTS operators beyond their initial knowledge of the system (i.e., considering work experience and education). A heuristic-based evaluation of both training programs identified few unique usability problems, suggesting the usability of the training programs did not interfere with the development of learner knowledge structures. Finally, on the basis of these results, a set of general guidelines for the design of the CTA-based training programs was developed. These guidelines included methods for structuring the components of the training program to support the three levels of SA and the amount of text that should be shown for each task.

Cognitive Task Analyses for Life Science Automation Training Program Design

by
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DEDICATION

To my mother for all of her help, support, and ideas.

BIOGRAPHY

Rebecca Green was born in Painesville, Ohio and raised in northeastern Kentucky. She completed her high school education at Mentor High School in 1998. She started with her Bachelors degree in Biomedical Engineering at the University of Pittsburgh with a concentration in biological systems and signals. While at Pittsburgh she worked on an automated medication dispenser design project, which precipitated her interest in human factors. In 2004, she received her Masters degree in Experimental Psychology at East Carolina University where she did research in neurological and cognitive psychology. Her research included work in a neurological psychology laboratory to study treatments for brain injuries and memory and a classroom research project that led to a thesis on computer-based tutoring methods. Since 2006, she has been working towards a Doctoral degree in the department of Psychology at North Carolina State University under the guidance of Dr. Dave Kaber and Dr. Chris Mayhorn. Her research interests include instructional interface design, cognitive modeling, and human-automation interaction.

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LIST OF ABBREVIATIONS

ACT-R	Adaptive Character of Thought - Rational
AH	Abstraction Hierarchy
CB	Computer Based
CCI	Critical Cue Inventories
CDM	Critical Decision Method
CELISCA	Center for Life Sciences Automation
CGA	Conceptual Graph Analysis
CoTA	Cognitive Oriented Task Analysis
CTA	Cognitive Task Analysis
CWA	Cognitive Work Analysis
DMSO	Dimethyl Sulfioxide
EPS	Effective Problem Space
FMS	Flexible Manufacturing Systems
GDTA	Goal Directed Task Analysis
GOMS	Goals-Operations-Methods-Selection Rules
HRV	Heart Rate Variability
HTA	Hierarchical Task Analysis
HTS	High-throughput Screening
ISD	Instructional Systems Development
LCD	Learner-Centered Design
LUO	Laboratory Unit Operations

LVR	Learner Verification and Review
OTJ	On-the-Job
PARI	Precursor-Action-Results-Interpretation
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
SC	Supervisory Control
SICU	Surgical Intensive Care Unit
SME	Subject Matter Expert
TATS	Task Analytic Training System
Tris-HCl	Tris-Hydrochloride
UCD	User Centered Design
VFR	Visual Flight Rules

INTRODUCTION

Over the past decade, high throughput screening (HTS) of biological compounds has become a central component in research and discovery programs in the pharmaceutical industry (Hamilton, 2002). Contemporary HTS processes involve chemical-based assays of organic and inorganic compounds for effects on human cellular functions, or enzyme reactions that are common in cells, as a basis for therapeutic development (Entzian, et al., 2004). Automation is used in HTS processes to increase the pace at which organisms can be tested for potential uses in biocatalysts for new drug development or industrial products. Time-consuming operations, such as pipetting (transferring) liquid extracts of test compounds into micro-culture plates, mixing compounds with reagents, etc. can now be performed by robots with the goal of increasing throughput, as well as enhancing test accuracy and promoting operator safety.

Early examples of pharmaceutical screening automation were based on microplate management systems. These systems were used in many laboratory unit operations (LUOs) integrating interchangeable robotic systems, but this approach limited throughput and the reliability of unattended operations was a problem due to less than ideal operations being assigned to robotic arms (Hamilton, 2002). A single articulating robotic arm, with interchangeable hands would typically perform all tasks from pipetting to sample transport (Figure 1). Unfortunately, liquid-handling work required frequent changing of manipulator attachments, when transferring to transport tasks. In an effort to make integrated, multiple-LUO, general-purpose robotic systems more reliable and capable of higher throughput, system designers began off-loading sample manipulation tasks from the robot arm to increasingly specialized workstations. The next technological development, specialized Cartesian-geometry liquid-handling robots, was the basis for the HTS systems in use today (Figure 2). Currently, through a combination of these modern robotic systems, data processing and control software, liquid handling devices, and sensor technology, HTS allows a researcher to effectively conduct thousands of biochemical, genetic or pharmacological tests in a short period of time (Cohen & Trinka, 2002).

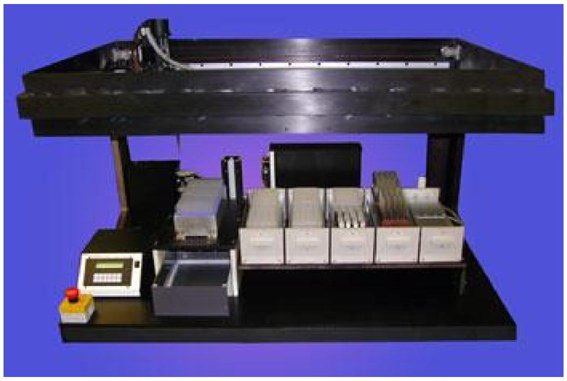

Figure 1. Historic robotic system with single process manipulator (J-KEM Scientific, 2002).

Figure 2. Example of modern HTS system.

Specialized biological screening tests, such as Trypsin inhibition tests, have been converted from traditional “bench-top” versions, describing how to manually perform a particular screening assay, to automated processes (Entzian et al., 2004). The trypsin inhibition test is a biochemical test that has been used to assess biological activity when screening crude extracts of marine microorganisms. These crude aqueous and organic solvent extracts are stored as a library of stock solutions. For the test, the stock solutions of the extracts are prepared by stepwise dissolution in two buffer chemicals, such as dimethyl sulfioxide (DMSO) and 0.05M Tris Hydrochloride (Tris-HCl). Cloudy stock solutions are then centrifuged and the clear resultant is used. Serial dilutions of the centrifuged solutions are prepared by a liquid handling device (e.g., 1:3) to achieve different concentrations (typically four or more). The principle of the test consists of the conversion of a chemical (i.e., BAPNA) to p-nitroaniline by Trypsin activity (a “yellow by-product”). The extent of absorption of p-nitroaniline can be determined at 405 nm by an optical plate reader. Inhibitory activity of extracts is measured as a decrease of absorption of the compound.

The Trypsin process has been automated at the University of Rostock (Germany), Center for Life Science Automation (CELISCA) using an integrated multitasking system. Samples, reagents, plates, and other consumables are supplied to liquid-handling instruments, detectors, and robotic plate manipulators. Scheduling software controls the flow of plates through the system and conducts the entire assay, under supervisory control by an operator. Automated testing of compounds involves several steps, including robotic pipetting of liquids (enzyme substrates, test compound extracts and other reagents) at different quantities and concentrations into micro-plates with many sample wells, incubating the micro-plates in an oven in order to elicit enzymatic reactions similar to those that would occur in the human body, and analyzing the reactions using optical measurement systems (Entzian et al., 2004).

Generally, biochemical assays can be transferred to an automated robotic system with a minimum of changes (Cohen & Trinka, 2002), but many of the details need to be reviewed to assure that the results will be consistent within a run, as compared to the same assay performed manually on the bench or at individual workstations. As a result, the role of human operators in this domain has dramatically shifted from manual material handling tasks to planning, controlling, and analyzing the results of automated screening lines. This shift in the role of the human operator has led to an increase in systems monitoring workload and a higher requirement for accuracy in operations performance, due to the need for greater attention to decision-making and error handling tasks as part of the HTS process.

Implications of Change in Life Science Processes for Training

The recent expansion of the knowledge base in clinical biochemistry has led to the development of sub-specialties within the broad discipline itself, including HTS (Rock, 1994). The emergence of new technologies in the domain of pharmaceutical laboratories has challenged traditional approaches to the education and training of laboratory technicians. Mocarelli (1994) outlines four factors or problems that affect the development and demands on training and education of biotechnologists. These factors include the fact that: (1) curricula differ among different countries; (2) the concept of the technologists' role differs from one country to the next; (3) there is difficulty in maintaining high professional standards in the face of rapidly changing technology; and (4) new applicants for the profession are in short supply. To address these problems, technologist training and education have evolved from solely on-the-job learning (prevalent in the infancy of laboratory technology) to semi-structured approaches in which professional education is available in academic institutions with specialized training occurring on-the-job.

The traditional on-the-job (OTJ) training, of new HTS operators usually consists of several weeks spent assisting a lead biochemist to become familiar with the methods and automation being used (Hamilton, 2002). This process is typically unstructured, which means there is no written documentation of the training procedures to follow and there are few objective means to measure task performance in order to ensure that all operators are trained to the same standard. On the other hand, the combined ‘core’ training programs in clinical biochemistry for medical and non-medical graduates have been structured for 2-year periods of training. The subsets of skills that technologists acquire through structured academic training include physiology and pathophysiology, application of biochemical tests, interpretation of results, selection of tests, control or analytical functions, laboratory management, and research and development (Mocarelli, 1994; Rock, 1994). Many of these are directly relevant to HTS processes. Academic training programs cover the theoretical background of clinical biochemistry and include those elements of medicine, physics, chemistry and mathematics that are necessary for a thorough understanding of the analytical techniques relevant to clinical biochemistry. Furthermore, a working knowledge of clinical laboratory information systems and principles of operations (systems) research has been considered relevant for rational analysis and planning.

The critical qualifications that clinical biochemists are expected to receive from formal academic education are based on the skills that are expected for performing technically demanding tests, evaluating methods and analyzing the findings in a traditional biochemical laboratory. However, in the domain of HTS of biological and chemical compounds for new drug component development, human operators are subjected to many performance and workload requirements in interacting with automated systems (programming and supervising), including preventing errors, that may extend beyond existing academic training. A successful HTS laboratory integrates several discovery steps including: target identification, reagent preparation, and compound management, assay development, and high throughput library screening (Cohen & Trinka, 2002). Biochemical laboratory technicians typically operate the HTS process by planning and programming robotic tasks, as well as delivering micro-plates, chemicals, plate labels, and pipetting resources (tip boxes, reservoirs, etc.) to a process line.

Due to the increased potential for errors related to the performance and workload requirements in such highly complex systems, training of the operators is recommended as one of the steps toward the successful development of new drug compounds, along with a good laboratory environment, and standard operating procedures (Cohen & Trinka, 2002). Cohen and Trinka suggest that because of the complexity and detail involved in the operation of fully automated screening systems, biological and chemical laboratories rely heavily on system and material supplier manuals and training programs to train new operators in using these systems. For this reason, most current training practices involve a combination of the review of operation manuals and documents, OTJ training, formal classroom training, and software tutorials.

A typical HTS experiment poses a high cognitive workload for supervisors, who must keep track of the timing of the process steps, whether chemical reactions are occurring safely, and whether robot motions are accurate (Kaber, Segall, Green, Entzian, & Junginger, 2006). Secondly, according to Hamilton (2002) the use of automation techniques to rapidly test large numbers of compounds places an even greater demand on the technician's ability to develop and conduct a perceptive analysis of the data being generated. Therefore, the operation of such highly complex systems requires that more attention be given to error avoidance, detection, correction, and reporting. Although operator and system errors are rather infrequent, occurring approximately once every 75 assay runs (Kaber, Segall, & Green, in review), their cumulative effect can be substantial. Fixing an equipment or resource error, like replacing damaged pipetting tool tips on a liquid transfer robot, or working through a series of error correction dialogs at the supervisory control interface for the HTS line, may only take a few minutes. However, other problems, such as a robot position error and collision with another line device may require a process engineer to visit the line or purchase new parts, which can take several days to correct. Depending on the time needed to correct a problem, errors can lead to delays in reactions or the need to scrap an entire experiment because of the limited life expectancy of compounds and enzymes. This is costly to the test facility because many of the organisms being investigated are extremely rare and the extracts are expensive to develop (Entzian et al., 2004). Furthermore, this can translate into higher costs associated with operator time, wages, and system materials.

The cognitive load imposed by a given task in HTS processes can be determined by such factors as attention to stimulus, stimulus rate and demands, and the degree of interactivity among task elements (Vidulich, 2003). Therefore, the limitations of working memory should be considered in instructional design for complex, dynamic systems. This is based on the assumption that a learner has a limited processing capacity and proper allocation of mental resources is necessary. Since learning involves the process of schema construction and skill automation, devoting mental resources to activities not directly related to schema construction and automation may inhibit one's learning. The development of schemata, involves the linking of information gathered by the learner through task experiences to rules associated with the task. Schemata become refined and more automated as a result of practice, and these modifications can decrease cognitive load during task performance. Therefore, training practice relative to task demands can provide learners with the opportunity to develop problem-solving schema that might reduce working memory demands during actual operations and lead to improved performance. The identification of the information processing requirements of the learner and the demands engendered by the task and automation can be achieved using Cognitive Task Analysis (CTA) methods as the basis for training program development.

Situation Awareness in Dynamic Systems

With the evolution of automation, many complex, dynamic systems have been created that require the ability of human operators to act as effective, reliable and timely decision makers. A dynamic system is one in which the state of elements in the environment is constantly changing as a function of time with complex interactions among elements (Endsley, 1995b). Situation awareness (SA) has been proposed as a cognitive construct relevant to decision making and task performance in a variety of complex, dynamic environments such as driving (Ma & Kaber, 2005), fighter aircraft piloting (Endsley, 1993), and small unit military operations (Strater, Endsley, Pleban & Matthews, 2000). Along these same lines, human exploitation of the complexities of automation for complex HTS operations is expected to be critically dependent on task SA and cognitive performance.

There are several competing theories of SA (Smith & Hancock, 1995; Vidulich, 2003). Smith and Hancock (1995) proposed an ecological theory of SA, in which it is defined as adaptive, externally directed consciousness. They indicate SA is the process of sampling, representing, and transforming results from the environment into knowledge and behavior outputs, while the processes themselves are neither knowledge nor behavior. The main limitation of this theory is that while a relationship between the elements in the environment and the knowledge and behavior outputs exist, they do not attempt to explain any causal mechanisms that account for the relationship. Vidulich (2003) describes SA as part of a “framework” theory because it seems to be a general concept used to describe and interpret a large number of previous studies into the human cognitive capabilities in complex tasks. The main limitation of this view is that it represents SA as an on-going process, continually changing, which is necessarily altered by any attempt at measurement. However, Endsley's (1995) theory has been successful in characterizing SA in other domains, includes an operational definition, and objective measures for assessment of SA. Therefore, Endsley’s definition and model of SA is adopted in this research.

Endsley (1988) defined SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future". This theory of SA is concerned with the mapping of the relevant information in the environment onto one’s internal mental representation of the situation and is heavily dependent on human information processing theory for explanation of the process (Endsley, 2000). In this conceptualization, SA is the integration and projection of the perceptual elements of the environment that result in decision and action selection outputs, which can be measured through subjective, performance-based, and physiological techniques.

Related to this, Endsley’s definition of SA can be broken-down into three separate levels, including perception, comprehension, and projection (Endsley, 1995a; Endsley, Bolte, and Jones, 2003). Perception of the environment concerns the status, attributes, and dynamics of relevant elements. Operator SA needs to incorporate information on the subset of elements in the environment relevant to current tasks and goals. SA requirements are those dynamic information needs associated with the major goals or sub-goals of an operator in performing tasks in a target domain (as opposed to rules, procedures, or static system knowledge) (Endsley, 1995a). The second level of SA focuses on operator understanding of the current situation based on integration of the perceived elements. This level depends on synthesis of the separate Level 1 elements and comparison of that information with the operator’s goals. The third level of SA is the ability of the operator to project future states of, and actions on, the elements in the environment. This level is based on a synthesis of the status and dynamics of the elements to form an understanding of the current situation (Levels 1 and 2) and the use of this information to predict future actions of the elements in the environment.

In summary, Endsley’s (1995) model of SA can be used as a framework for identifying SA requirements (elements) for dynamic systems control at various levels of cognitive processing in complex task performance, such as HTS operations. SA requirements can be determined based on task analysis methodologies such as goal-directed task analysis. SA requirements focus not only what data operator's need for performance, but also on how that information is integrated or combined to address each decision within HTS. Training programs directed at improving operator SA can then be generated by identifying the important SA requirements. Endsley's (1995) definition and model of SA is adopted in this research as it is the only current theory of SA that has been operationalized for global assessment of complex system operator behavior through objective measures (e.g. dynamic knowledge questionnaires).

Overview of Task Analysis Methodologies

In order to address the potential for costly errors in HTS processes, the functional limitations of HTS automated devices, with respect to process goals and operations, need to be identified (e.g., historical LUOs automation). The required behaviors of biochemists in planning, executing and analyzing the results of HTS operations, as well as programming the lab automation and equipment used to facilitate these operations need to be identified to support enhanced training programs allowing humans to effectively supervise and control automation in critical situations (e.g. during troubleshooting). In this research, task analysis methods will be used for these purposes.

Chipman, Schraggen, and Shalin (2000) classified task analysis into two major categories, including traditional task analysis, and CTA. Traditional task analysis is a systematic breakdown of a task into its elements, including a detailed description of the activities as part of the task and element durations, task frequency, task allocation between human and machine, task complexity, and any other unique factors involved in, or required for, the performance of a given task (Chipman, Schraggen, & Shalin). Diaper and Stanton (2004) provide a more general view of task analysis, as the description of the performance of work to achieve goals. They indicate that task analyses produce one or more models of the world; where such models describe the task and relationships between the task elements. The level of detail in a task analysis ranges from high level descriptions, such as those found in job analysis (identifying the key responsibilities, skills, knowledge and aptitudes), through detailed task inventories (identifying the sub-tasks that are critical for knowledge structure composition and system design). As one example, the task description approach to task analysis, is composed of qualitative verbal statements or descriptions of tasks, usually in essay form, which lack the precision necessary for completely describing jobs (Jonassen, Tessmer, & Hannum, 1999). In this depiction of the task, there is an emphasis on the observable behavior when describing a task; it indicates what a person does when performing his or her job, but does not focus on cognitive requirements, such as decision making. Therefore, traditional job or task analysis methods are not particularly well equipped to investigate cognitive processes underlying tasks.

CTA on the other hand, is an analysis of the knowledge, thought processes, and goal structures of cognitive tasks (Hollnagel, 2003). It has been used to design new system interfaces, in cognitive engineering of human-machine systems, to develop expert systems, for operator selection, and for training purposes (Wei and Salvendy, 2004). Some of the more common CTA methods currently in use for instructional design include: cognitive interviewing techniques, Goals, Operators, Methods and Selection rules (GOMS), the Critical

Decision Method (CDM), and Precursor-Action-Results-Interpretation (PARI) (Hollnagel, 2003; Jonassen, Tessmer, & Hannum, 1999). For example, CDM can be applied to modeling dynamic tasks characterized by high time pressure and information content through the use of probes eliciting reasons for perceptual discrimination, judgment rules, and critical cues used by domain experts (Klein, Calderwood, & MacGregor, 1989). Further, in PARI, an expert is presented with a problem, he attempts to identify each action (or decision), the precursor (or perceptual cues) to that action, the result of that action, and the interpretation of the results of the action (Jonassen, Tessmer, & Hannum, 1999). The expert is then asked to elaborate on their solutions, focusing especially on reasoning that they use in making their decision about what to do. Therefore, CTA can be a useful tool for identifying operator dynamic goal sets, factual knowledge stores, mental strategies, critical decisions, and situation awareness (SA) requirements as a basis for new human-machine interface design, for critiquing existing interfaces, processes, and systems, or for training development.

Focus on CTA Methods for Training Design

Task analysis for instructional design is a process of analyzing and articulating the kind of learning that a trainee will be expected to exhibit in task performance. In order to design instruction that will support learning, it is essential that we understand the nature of the task learners will be performing, including both the behavioral components of the task as well as the information processing components required directly before, during and directly after performance. Therefore, there is need for the selection of CTA methods in the support of the training of operators in complex domains such as HTS. Several CTA methods could potentially be used to develop training for operators of HTS systems including: Precursor-

Action-Results-Interpretation (PARI), Critical Decision Method (CDM), Goals-Operations-Methods-Selection Rules (GOMS), Goal Directed Task Analysis (GDTA), and Abstraction Hierarchy (AH) modeling.

The first method, PARI, pairs two experts in an interview setting, such that one creates a problem containing performance faults (found in the real world) and the other generates a series of actions that represents a solution path (Lajoie, Azeveo, & Fleiszer, 1998). The purpose is to engage experts in verbalizing their purposes, actions, reasoning, and interpretations as they solve the problem. During this process, the experts are probed for the assumptions behind their actions while they are solving the problems posed to them. Having identified the activities, results, and reasoning used by the experts, novices will be presented with the same problem to find the areas of the decision making process where their methods differ from the expert as the basis for instruction. PARI integrates system, procedural, and strategic knowledge and associates them with system actions. This methodology is most useful for analyzing complex, situated problem solving tasks, especially troubleshooting tasks. Furthermore, it assumes that the expert problem solvers possess an integrated and well-instantiated mental model of the system they are troubleshooting.

CDM (Klein, Calderwood, & MacGregor, 1998), on the other hand, is a semi-structured interview technique that uses cognitive probes in order to elicit information regarding expert decision-making. This method is an extension of the Critical Incident Technique (Flanagan, 1954), which was developed in order to study the naturalistic decision-making strategies of operators in complex, dynamic systems. This methodology can be used to elicit specific information regarding the decision making strategies used by experts during a previous task and the output can be used to construct propositional networks which describe the knowledge required during the scenario under analysis. However, concerns have been raised with respect to the reliability of the retrospective analysis of scenarios, the fact that the data obtained is highly dependent upon the skill of the analyst and the interviewee, and the verbal reports used to reconstruct events may not accurately represent the cognitive processes of the decision being made.

The third method, GOMS (Card, Moran, & Newell, 1983), is used to define a user's goals, decompose these goals into sub-goals, and demonstrate how the goals are achieved through methods, task operators and selection rues applied to interaction with the target system. This methodology can be used to provide a description of how a user performs a task, to predict performance times, and to predict human learning. The methods as part of GOMS analysis allow the analyst to describe a number of different potential task routes. GOMS is typically used only for modeling HCI domain tasks. Furthermore, the modeling technique does not permit environmental context to be taken into consideration in the description of methods, and it is limited to modeling error-free, expert performance. Beyond this, GOMS models do not account for either learning of the system or its recall after a period of disuse and they also do not account for possible errors.

GDTA focuses on the basic goals of operators, the decisions that need to be made to accomplish these goals, and the SA or information requirements for each decision (Endsley, 1993). It seeks to document what information operators need to perform their job and how the operator integrates or combines information to address a particular decision. The experts are typically presented with a task scenario and asked to describe their performance in the absence of any existing automated support systems. However, the analysis is based upon operator goal states in the scenario and not on specific states of the task environment or support systems. This analysis also does not reflect the characteristics of technology an operator may be required to use.

Endsley (1993) presented an analysis of the SA requirements for fighter aircraft pilots involved in air-to-air combat missions using a series of analyses, including GDTA. GDTA was used to ensure that the list of primary goals, sub-goals, and SA requirements collected during unstructured interviews with pilots were correct and complete. One of the important characteristics of this assessment is that it focused on what the fighter aircraft pilot needed to know, not how or when they should receive information. Relevant to this, the importance of pilot goals shifts throughout the course of a mission due to external events, changing some primary goals to secondary goals. Endsley included the list of SA requirements identified through GDTA in a rating questionnaire asking pilots about the general importance of requirements to air-to-air fighter missions. The ratings revealed a clear picture of what aspects of environment perception, comprehension and projection were considered critical by fighter pilots.

The method of GDTA was also applied by Usher and Kaber (2000) to analyze supervisory control (SC) of flexible manufacturing systems (FMS) and to identify controller information requirements as a basis of interface design. They demonstrated the potential effectiveness of GDTA models for identifying information needs and requirements in the manufacturing domain. These information requirements were then used to develop guidelines for the design of supervisory control interfaces (Usher & Kaber). One of the important characteristics of this analysis was that the results of the GDTA were used to establish general information requirements for a generic task context (SC of any FMS) as apposed to information on a specific type of system. This resulted in a broader range of detail on the information requirements compared to other analyses.

The AH method of analyzing work domains is used to extract operator information requirements for a system, constraining relationships among system functions, multivariate relationships, and means-end relationships between system components and their functions that can be used as a basis for determining optimal performance (Bisantz & Vicente, 1994). AH modeling is an effective tool for revealing how complex system processes and functions are facilitated through specific components and can provide explanations of why certain components are needed to achieve system purposes. It is particularly suited for identifying information needs of operators in critical error situations. However, being an event independent tool, the capability of an AH to reveal difficulties in specific task performance is limited.

Mazaeva and Bisantz (2007) presented a description of the application of work domain analysis using AH models to represent an automated system; a camera. They compared the AH models with another method common in work domain analysis, in terms of the information made available through the model and the tasks that could be accomplished on the basis of the model. One major difference they pointed out between AH models and other CTA methods is the presentation of information on constraints within the structure of the domain versus within the structure of a task. Secondly, AH models provide information on the specific structures and components that are used for control of the automation and how they supported system functions and purposes versus information requirements needed for successful control of tasks, as found through other methodologies. Therefore, these differences are important to training operators of automated systems as the content of AH models can be used in training programs that focus on principles regarding system operation.

In conclusion, the identification of the information processing characteristics of operators and the demands engendered by tasks, as bases for training program development, may be achieved through a combination of CTA methods. Among the available CTA methods, the combination of GDTA and AH modeling may be of greatest use in the design of effective learning systems. The GDTA can be used to identify high-level goals, and complex information content needs of operators that should be supported by a training program. AH equipment and automation models can be used in training to describe to operators how each equipment function is implemented on a screening line and the purpose of the various subsystems and components of devices relative to operator goals. AH models of automation can be used to teach operators how the functions of each device are implemented through software and the purpose of various interface features. Use of these methods for such training purposes has not been formalized or evaluated.

Need for Cognitive Task Analysis for Training Design

Historically, industrial job training has been accomplished largely through on-the-job observational learning and apprenticeships (Clark & Estes, 1996). However, these methods have been found to produce variable results due to a lack of knowledge of the critical behaviors that should be emphasized for the trainee and that some critical steps or decisions occur rarely and are inefficient to observe in real time. Related to this, traditional task analysis methods utilized in training systems design have focused on observable behaviors and ignored the impact of cognitive process and structures, such as problem solving and decision-making as mentioned above. However, with the changing organizational climate for HTS training, overt-behavior based task analyses do not adequately provide the information required to perform more cognitively complex jobs and tasks as part of biological research operations and OJT may not provide the level of training stability across operators needed to ensure process quality.

Previous research has indicated that task analysis can be used to describe any one of four types of fundamental structures for specifying the information content in traditional Instructional Systems Development (ISD) including: (1) the learning hierarchy, (2) the procedural hierarchy, (3) the learning concept taxonomy, and (4) the model of the learning requirements (Gagne, Briggs, & Wager, 1992; Reigeluth, Merrill & Bunderson, 1978). In this way, task analyses support five classes of learning outcomes as identified by Gagne, Briggs, and Wager (1992), including: intellectual skills, cognitive strategies, verbal information, attitudes and motor skills. Traditional task analysis provides information pertinent to the goals, methods, and supportive prerequisites for development of learning and procedural hierarchies, but does not provide information regarding the cognitive learning concepts or help in modeling learning requirements for complex or high workload tasks.

Another factor in training system design supporting the need for CTAs is understanding cognitive processes and structures that support the development of expertise at work. Unfortunately, traditional ISD methodologies have provided few insights or guidelines for the analysis or training of complex cognitive skills, those involving decision-making, that demand a high level of performance, and that involve high workload. For effective training there is a need to identify expert or novice knowledge structures and to determine specific gaps in cognitive skills that must be addressed for performance by taking advantage of CTA methods. The gap in cognitive skills is typically identified through an initial or entry test to assess starting knowledge (Dick, Cary, & Cary, 2005). This has been demonstrated by researchers working within the field of cognition, which view experts and novices as having developed qualitatively and quantitatively different knowledge structures and processes about tasks within their domain of experience. Therefore, training design that includes CTA methods would be effective in capturing the components of complex tasks that rely on cognitive skills, such as decision-making and problem solving across levels of expertise.

The general challenge of CTA is to capture the types of knowledge used to perform all work tasks, even the most complex. Clark and Estes (1996) indicate that CTAs are an effective alternative in training because they focus on the knowledge type and not necessarily the format of the knowledge. This may be particularly important as the format of knowledge (in terms of images, propositions, and linear orderings) in many of the traditional training approaches could influence the way knowledge is learned through training and it may be necessary to change the format depending on the type of trainee. The main point here is that CTA is needed to reveal cognitive skills and address different levels of expertise in training program design.

Integrating CTA in Training Design

According to the Clark and Estes (1996), a major tenet of the use of CTA in training is that knowledge takes different forms, which enable different performances at different levels of expertise, requiring different amounts and types of training methods. In fact, they suggest that when mental models used by experts can be elicited and represented by CTA, they can then be taught to others in order to promote consistency in system performance across operators. A wide variety of CTA approaches have been identified, however, and the differences among approaches tend to be based more on the specific nature of the types of tasks targeted for analysis and the eventual use of the information being collected. Several techniques for the development and testing of training systems discussed by Clark and Estes are GOMS, PARI, and ACT cognitive task analyses. Anderson, Corbett, Koedinger, and Pelletier (1995) review their previous work on developing computer-based cognitive tutors and evaluations of tutors for geometry, algebra, and programming skills in LISP. Their work was based on the ACT-R theory and cognitive modeling methodology and written as a system of if-then production rules capable of generating the multitude of solution steps behind successful and near-successful student performance. The background cognitive model serves to match student actions to those the model might generate and to monitor students' learning from problem to problem. The evaluations of these cognitive tutors have tended to demonstrate significant achievement gains for the tutor compared to paper and pencil instruction. Clark and Estes suggest that the identified CTA methods are best suited for structurally organized, rule-based performance systems by suggesting to trainers efficient ways to chunk actions and procedural steps in decisions that need to be learned together in the formation of automated “productions.” This is particularly important for many of the tasks encountered by HTS operators, as performance is often rule-based during the planning and analysis stages of such processes.

Ryder and Redding (1993) provide a framework for the integration of cognitive and behavioral task analysis methods within the ISD model, including front-end analysis, but they did not provide connections between the components of the task analysis methodologies and the instruction content. They suggest that their CTA-based ISD framework supports development of training programs that build a flexible knowledge base, efficient mental models (or task understanding) and decision making skills, especially for dynamic situations. Unfortunately, they did not address how to incorporate CTA methods for evaluating cognitive skills within the testing and evaluation phases of ISD.

Related to this, Gagne, Briggs, and Wager (1992) provide a methodology for identifying and classifying instructional content resulting from methods like CTA with respect to the target domain and supporting training objectives in the form of learning hierarchies. The results of the CTA identify the concepts that must be learned as components of behaviors required by the target task along with the supporting or enabling objectives that lead to the target performance goal. The prerequisites identified in a learning task analysis can be classified, in general, as essential or supportive prerequisites and can serve as a guide in the design of a sequence of instruction and the planning of instruction assignments (Gagne, Briggs, & Wager, 1992). Other research has indicated that learning hierarchies resulting from task analyses can serve as the basis for the planning of instructional sequences and the different instructional strategies (Reigeluth, Merrill, & Bunderson, 1978). However, it is important that an instructional designer select those structures from a CTA relevant to the target training task and then apply a framework for organizing instructional content.

Seamster, Redding, and Kaempf (2000) indicate that a CTA is usually performed as an extension of a "front-end" analysis on a system. This is the initial gross level analysis of the task or job to clarify difficult to observe activities at the task or subtask level. In their chapter, Seamster et al. indicate that CTA methods can be used as part of the front-end analysis for knowledge requirement identification, curriculum design, and instructional technique selection as part of an ISD framework. The front-end analysis is the starting point for categorizing skills by training type, identifying key novice-expert differences, and identifying team skills versus individual skills. The CTA extension provides a foundation for the systematic design of training processes and devices, including a taxonomy of knowledge and skill types, which have implications for the training process, specifically, organization of training requirements. The CTA can identify the knowledge or skill content required for different stages of subtask performance development.

Dubois (2002) provided four steps in the process of conducting CTAs within the front-end analysis of ISD: planning, knowledge elicitation, knowledge representation, and application development. The planning component entails a series of four key decision points: purposes, methods, sampling procedures, and project personnel. The choice among CTA methods rests on two main criteria, matching the method to the situation and evaluating trade-offs between costs and benefits; however, all methods can reveal useful information about both the content and processes of cognition. Dubois identifies two categories of knowledge elicitation methods, interviews and protocol analyses. The author indicates that the Critical Decision Method (CDM) and PARI are two examples of interview techniques, and Cognitive Oriented Task Analysis (CoTA) and team communication analysis are two examples of protocol analysis. Each of these methods differ slightly in terms of the goals, assumptions, strategies and implementation of the knowledge elicitation techniques. The knowledge representation provides an efficient summary of knowledge elicitation results organized in a format that is appropriate for the training-application development phase. The specific method determines the representation chosen, optimal structure, amount of detail, and completeness of the knowledge representation. The three general methods of representation described by Dubois are textual tabulations, graphics, and simulations or models. Therefore, the determination of the optimal structure and the content of a training program (such as the use of simulations) is a product of the knowledge elicitation techniques selected for training program development. The final step of applying the CTA results involves formally incorporating knowledge requirements and task requirements into training content and for determining strategies of training. The CTA provides content for scenarios, question content or error information, and information on how the procedures and standards may differ in different contexts, or how cues initiate and guide implementation.

Training curriculum design typically follows front-end analysis and uses the CTA results to define the performance or training objectives, instructional sequences, content, and the specification of performance assessments (Gagne, Briggs, & Wagner, 1992; Jonassen, Tessmer, & Hannum, 1999). CTA results can inform the sequencing of knowledge and skills through the mapping of knowledge and skill types onto a framework of learning outcomes as described by Gagne et al. (1992). Secondly, the CTA can provide a basis for determining the common content that should be presented across several work team members, such as in aviation operations (e.g., Endsley & Garland, 2000). Furthermore, CTA methods can be used at the detailed subtask level to identify the decision-making skills and strategies necessary under critical conditions or for less practiced activities.

There are a wide variety of purposes, contributions, and applications of CTAs and selection of the optimum methods depend on the purpose for doing a CTA, the constraints, and the resources available (Jonassen, Tessmer, & Hannum, 1999). CTAs are especially suited to training development because the knowledge requirements, or the facts, concepts and procedures that support task performance, and the decisions, cues, judgments, and perceptions that contribute to effective performance are directly addressed with these techniques. An explicit set of knowledge requirements can be used to diagnose performance deficiencies and prescribe useful strategies for overcoming obstacles. These knowledge requirements can also be incorporated into training performance assessment, such as in decision-making tasks, by separating decisions about goals and decisions about methods (used to achieve goals) and thereby preventing method fixation. The methodology then allows for determination of the effectiveness of operators in achieving goals and executing methods.

Finally, Seamster, Redding, and Kaempf (2000) provide a set of guidelines for translating the task analysis derived skills into a form useful for training development and evaluation, which include: (1) specifying observable behaviors in terms of simple actions, (2) validating observable behaviors with actual users, and (3) organizing observable behaviors by event sets to produce more reliable assessments of performance in training. Furthermore, training processes and devices need to be systematically designed and allocated based on the specific types of knowledge and skill being trained. To support this process, Seamster, Redding, and Kaempf provide examples of the mapping of knowledge and skill types to frameworks for learning outcomes and training techniques. They provide a list of the types of aviation knowledge and skill types classified according to Rasmussen's (1985) skill, knowledge, and rule based learning as well as Gagne's five learning outcomes (Gagne, Briggs, & Wager, 2002). This work and the other studies on incorporating CTA in training systems design provide a basis for addressing complex cognitive skill development in domains like HTS.

Clark and Estes (1996) indicate several questions that need to be addressed in the application of CTAs for training development, including: the relation of the types of knowledge identified by CTAs to the support of training performance, identification of efficient and valid CTA methods, and the measurement of the cost-effectiveness of methods. They present a number of questions relating to the varieties of declarative and procedural knowledge and how these two types of knowledge interact in the operation of complex systems and how they should be effectively presented through training system design.

Current Research Applying Task-Analysis to Training Design

Although Seamster, Redding, and Kaempf (2000) discuss the application of CTA results to front-end analysis, curriculum design, and instructional technique selection, these are not the only areas in which CTA results can be applied successfully for supporting training. Several examples demonstrating the current views and methods of task analysis, as it is applied to training program design are available. These include the use of the CDM (O'Hare, Wiggins, Williams, & Wong 1998), a task analytic training system model for on-the-job training (Walter, 2000), and the use of PARI to structure training programs (Lajoie, Azeveo, & Fleiszer, 1998; Schaafstal, Schraagen, & van Berlo, 2000).

O'Hare, Wiggins, Williams, and Wong (1998) present three case studies demonstrating the use of CTA methods to support the development of training and the design of displays. The approach taken by the authors was a modification and extension of the CDM approach for the identification of the goals, cues, expectancies, and courses of action in three target domains. In this approach, participants recalled an incident in which their expertise made a difference to the outcome and they emphasized situational assessment components of decision-making in the knowledge elicitation process. To support the process of identifying the situational awareness and planning aspects that are important to this type of knowledge and performance, the authors revised and extended the cognitive probes from the Recognition-Primed Decision (RPD) model (Klein, Calderwood, & MacGregor, 1989).

In the first case study, the authors interviewed expert white-water rafting guides on problematic situations where their expertise was used to make critical decisions in determining the raft's direction and the safety of the raft's occupants. Following the interviews, the timelines and decision points were summarized into situation assessment records, which contained a breakdown of their decision strategy in terms of the cues, expectancies, consequences, and courses of action. The critical incidents reported contained a combination of intuitive and analytical modes of decision-making, consistent with the RPD model. However, the authors indicate that the questioning of experts failed to adequately differentiate between the recall of specific incidents for use in problem solving or use of a generalized mental prototype scheme to aid in decision-making. The implication of these results for guide training is that training design, based on CTA methods, can be specifically tailored to enable guides to recognize pertinent cues in the environment that may be indicative of potential danger while avoiding distraction or irrelevant information. The authors developed a prototype multi-media package to demonstrate the cue recognition of expert river guides. This tool presents brief video segments of rafts traversing a series of rapids in which the participants are required to stop the video when they are able to predict the course of the craft through the water. This was found to be an effective method for training critical decision skills identified by the CTA methodology.

In the second case study, O'Hare et al. (1998) examined the skills required for successful 'visual flight rules' (VFR) flying. In this domain, experienced general aviation pilots were asked to recall an in-flight situation requiring an unusual and difficult decision with regard to the weather. Critical cue inventories (CCIs) were then constructed for each of two meteorological phenomena. The results indicated a high degree of consistency between experts regarding the critical cues for action, suggesting the use of automatic processing for successful task performance. In developing training for novice VFR pilots, the authors offered that practice should be provided for learning the cues necessary to develop perceptual differentiations used by experts. The authors developed a multi-media weather-related decision-making tutoring system based on the output from a Conceptual Graph Analysis (CGA) with the expert pilots. The tutoring tool consisted of two parts, a declarative knowledge section, in which the learner' was given information to help them recognize the cues involved, and a procedural skill section to help participants make cue comparisons and receive feedback. The main advantage of the use of the CGA with the CTA in this case was the description of the direction and nature of the relationship between learning concept nodes through the graph. The combination of methods provided a clear framework within which to interpret the results of the CTA.

In the final case study, the authors demonstrated the use of the CDM for determining display requirements for a computer-based system to replace a manual ambulance dispatch system. In this study, expert dispatchers were asked to relate a particularly unusual and challenging incident and then identify the sequence of events and decision points. Four main goals were identified and organized according to their information value (i.e., maintain situational awareness, match available resources to the needs of the situation, get help on the way within 3 minutes, and maintain record of events). They were then used in the development of a training curriculum that emphasized the tasks involved in developing and maintaining SA. The redesigned ambulance dispatch displays portrayed information to support the decision strategies of operators involved in determining the current state of resources and matching them to the needs of emergency situations.

All three of the applications discussed in this study demonstrated domains in which decisions must be taken within a short amount of time in response to critical environmental cues. Furthermore, these case studies provide helpful suggestions on how the results of CTA can be used to drive the development of training methods. They indicate the importance of identifying critical cues for developing effective decision-making skills and reveal how all CTA methods can lead to the development of improved training systems or display designs. Unfortunately, the authors did not provide any system for directly linking the results of specific CTA methods to the components of their training systems. This process needs to be made explicit in future research.

In a study by Walter (2000), a task analytic training system (TATS) was used for developing a structured on-the-job (OJT) program for aviation maintenance and inspection personnel. The existing aviation maintenance training program was based on a 'buddy system', it was generally unstructured, and it was conducted away from the actual work site, similar to the current approach to biologist training in HTS operations. Structured on-the-job training was necessary in this environment due to several factors including, the practice of job bidding, the local features of the work environment affecting task completion, the gap between training manual procedures and realistic operating procedures, and the requirement of close team cooperation. Therefore, the TATS model was used to provide a generic, performance-based approach for developing comprehensive and structured training. The elements of the TATS model included: needs analysis, outlining targeted job(s), writing and verifying training modules, an approval system, sequencing training for individualized programs, implementing programs, and debugging and evaluating plans (Walter, 2000). The TATS design team performed task analyses or job-task breakdowns until the team decided that all tasks could be taught and learned in a half-hour, each task was later written-up as individual training modules. The identified tasks were ranked according to frequency, criticality, difficulty, and safety concerns to allow the teams to address the more critical elements or tasks first. The resulting modules were described as containing a cover sheet with a performance objective, trainer preparation, special requirements, prerequisite models and a three-step job instruction training procedure. The instructions were written in a two-column format to promote quick task referencing. At the conclusion of training, evaluation questionnaires were given to both trainees and trainers consisting of open-ended and attitude questions.

Interestingly, this study presented training program needs that are similar to the issues identified with traditional HTS system operations, including the need to support operators in high workload conditions and system error prevention. Furthermore, Walter (2000) presented a framework for the development of training and the presentation of materials to address such issues. However, his methodology was not as task analytic as some of the more common task analysis methods used in ISD (e.g., CDM; Jonassen, Tessmer, & Hannum, 1999). In any case, the research demonstrates how task analysis can be used to effectively structure an OJT program and it provided insight into specific elements of training that are supported by task analysis.

The next two studies demonstrate the most commonly used task-analysis methodologies in ISD. In these studies, the PARI method is used to structure a troubleshooting system and for the development of complex technical skills. The process of troubleshooting, or symptom identification, fault determination, and compensatory actions, is often carried out under time pressure, and is a complex task with a high turnover among expert troubleshooters. Therefore, a study by Schaafstal, Schraagen, and van Berlo (2000), developed a new method for the training of troubleshooting, labeled “structured troubleshooting”, which combines a domain-independent strategy for troubleshooting with a context-dependent, multiple-level, functional decomposition of systems. The design of the new training method involved an iterative process of observation, consultation with training practitioners, and literature review. CTA methods were used in both the observation and consultation stages.

The first component used in this study included a CTA, consisting of two preliminary observational studies on troubleshooting in two systems: a radar system and a general computer system (Schaafstal, Schraagen, & van Berlo, 2000). The second component, used a think aloud process as a method for observing technician troubleshooting strategies. This process identified gaps between theoretical instruction and application of knowledge and a lack of functional thinking. The troubleshooting strategies were classified into categories, based on PARI, including observations, hypotheses, testing, and conclusions.

The resulting training program consisted of a top-down and hierarchically structured approach instead of a list-oriented approach. Evaluation of the training program consisted of three parts, a verbal protocol process while troubleshooting, a theoretical knowledge test consisting of open-ended questions, and a subjective evaluation of the training program. The results of the structured development of the training program indicated that the new approach improved performance, especially for novices. Moreover, the authors observed that structured troubleshooting can be taught in less time than traditional troubleshooting, ultimately leading to a reduction in training and troubleshooting costs. In this study, multiple CTA methods (observational study and think out loud) were used to support the training design approach. Therefore, there is a need to explore other combinations of existing CTA methods for supporting training program design for complex cognitive systems.

A final study involved research investigating variables related to decision-making and the instruction of technical skills in a surgical setting. Traditional instructional design approaches often teach factual knowledge without a mechanism for contextualizing it in situations that would make abstract principles more concrete (Lajoie, Azeveo, & Fleiszer, 1998). Therefore, Velmahos, Toutouzas, Sillin, Chan, and Clark, et al. (2004) indicate that to achieve optimal effectiveness, a technical skill should be taught in a detailed, step-by-step, standardized, analytical fashion that allows in-depth comprehension of the essential elements of the technique. In the study by Lajoie, Azeveo, and Fleiszer (1998), they presented a process for converting PARI task analysis methods into a computer-based training program as a way of examining the types of decisions nurses make in a high information flow environment, such as a surgical intensive care unit (SICU). The PARI approach was used to isolate the types of cognitive skills required to perform in the SICU and then these skills were coded into a computer based (CB) learning environment for medical personnel. In this way, the learning content was delivered in a structured manner, as advocated by Velmahos et al. (2004).

Findings from previous research on expert-novice skills have contributed to the understanding of how novices progress to experts through conditions of learning of skill acquisition and the types of skills that differentiate the expert from the novice learners in complex problem solving domains (Gagne et al., 1992). In the Lajoie, Azeveo, and Fleiszer (1998) study, the PARI methodology was used to elicit think-aloud responses as nurses diagnosed cases. The verbal protocols were coded according six stages of clinical decision making: hypothesis, planning, actions, results, interpretation, and solution paths. They were then used to construct decision trees to represent the critical aspects of each nurse's clinical decision making. A modified effective problem space (EPS), or idealized decision-making process, was developed for interpretation of the correct diagnosis. The EPS decomposed nurses' decision making into plans and actions. The EPS revealed an ill-structured nature to the nursing tasks and that there was no best way to assess a patient. However, a method could be developed to teach novices to be more systematic in their clinical problem solving skills, similar to experts.

The instructional system described in the Lajoie, Azeveo, and Fleiszer (1998) study was an adaptive computer-based instructional system consisting of four components, the expert module, a student module, a tutor module, and a student-machine interface (for review). The modules contained a menu system to replicate the modified EPS and allowed nurses to indicate and follow-up on plans with specific data collection actions. Once a specific data collection action was selected, the tutor prompted the nurses on goals, which were tracked based on their subsequent actions in order to see how goals were confirmed or disconfirmed. Several options were also available to support the nurse's decision making through entry of a list of three differential hypotheses (diagnoses), their degree of confidence for each diagnosis, and a solution trace to compare their strategy to an experts' solution trace. The tutor design used dynamic assessment of the learner in the context of problem solving. Assessments were made of the learning process rather than the learning outcomes. The evaluation of the SICU tutoring environment elicited input from experts using the system regarding the validity and authenticity of the environment, information regarding the user interface, and pre- and post-tests to assess the knowledge presented in the prototype. The expert evaluator was found to explore the patient more thoroughly and in a more systematic manner from pre- to post-test assessment. Furthermore, the learning solution trace of the expert evaluator showed strategy differences in clinical decision making, as well as the types of goals selected, and actions taken to complete a goal, compared to what might be expected from the learning solution trace of a novice.

All of these research examples demonstrate how task analysis, as it is applied to training program design, can be an effective means of providing timely and adaptive tutoring interventions while dealing with variability in user learning approaches, and differences in complex task domains and learning environments. In addition, the work shows the benefits of task-analysis-based training programs on the amount of time required for training, the efficiency of technicians in performing their jobs, and the cost of training time. In conclusion, while task analysis methods are traditionally used in the front-end analysis of ISD for the initial, gross level analysis of the task or job, little research is available that directly links the results of CTA methods to the development of training system components. Some tutoring systems have been created based on the results of task analytic approaches but no standardized methods exist for relating outcomes of specific CTA methods to elements of training programs. Some studies have integrated multiple CTA methods to support training program design but additional research is needed on contemporary CTA methods such as GDTA and AH models for training HTS processes.

Utility of Contemporary CTA Methods for Training Design

This section presents a review of contemporary CTA methods, including GDTA and AH modeling, and outlines an approach to integration of the results of the two techniques. The review of the knowledge requirements available through GDTA and the factors underlying SA in the performance or training of complex tasks is addressed in the first section. Secondly, a review of the system components and resources as modeled by AH is addressed. Finally, an outline of the integration of the two CTA methods, as a basis for developing training programs, is provided.

Knowledge Requirements Analysis Through Goal Directed Task Analysis (GDTA)

Several methods have been developed through cognitive engineering research to identify detailed information requirements for operators of complex systems in the performance of general functions and tasks. One such methodology, goal-directed task analysis (GDTA) is a SA requirements assessment methodology developed by Endsley (1993) and originally demonstrated in the aviation domain. The method focuses on identifying operator perception, comprehension and projection requirements in performing complex systems control. The results of a GDTA include lists of critical operator decisions and SA requirements that can be used as a basis for defining appropriate content of complex system information displays, as well as for training program content development, development of SA assessment measures, and operator selection (Endsley, Bolte, & Jones, 2003).

The general steps to conducting a GDTA include identifying the users' major goals, the sub-goals to support overarching goals, operational tasks to achieve sub-goals, questions that are part of decision making in task performance, and information requirements to answer these questions (Usher & Kaber, 2000). This information is elicited from a domain expert in a series of structured interviews. The experts typically describe their performance in a task scenario without making reference to the use of existing automated systems or software. The analyst then creates a goal tree (or hierarchical outline) describing the goals, sub-goals, and information requirements, independent of the technology that may ordinarily be used (Endsley, Bolte, & Jones, 2003).

Due to high workload demands on operators in the HTS domain, Kaber et al. (2006) hypothesized that the use of CTA would provide a better understanding of complex system operator needs and could serve as a basis for enhanced control interface design. The GDTA was used in this research, as it addresses the needs of operators to manage high workload in a dynamic environments, achieve and maintain high SA, understand complex operations needs, and process high information content tasks and displays. Figure 3, presents a diagram from Kaber et al. (2006) of the overarching goal and all major sub-goals, as part of discovering compounds leading to drug derivative development by operators of HTS systems. The major goal of the lead operator of the HTS line was identified as the discovery of compounds with the potential for development into drug derivatives. A sub-goal as part of adapting the bench-top method to the HTS line is to identify which types of micro-plates are to be used in the assay. The specific tasks to this sub-goal include, for example, determining the best well configuration for sample plates and determining whether the volume of test micro-plates is acceptable for the assay. Critical questions or operator decisions were also elicited. Once this analysis has been completed, it forms the basis for understanding the factors that will support operators in achieving a high level of SA across different task requirements, as needed in meeting each goal.

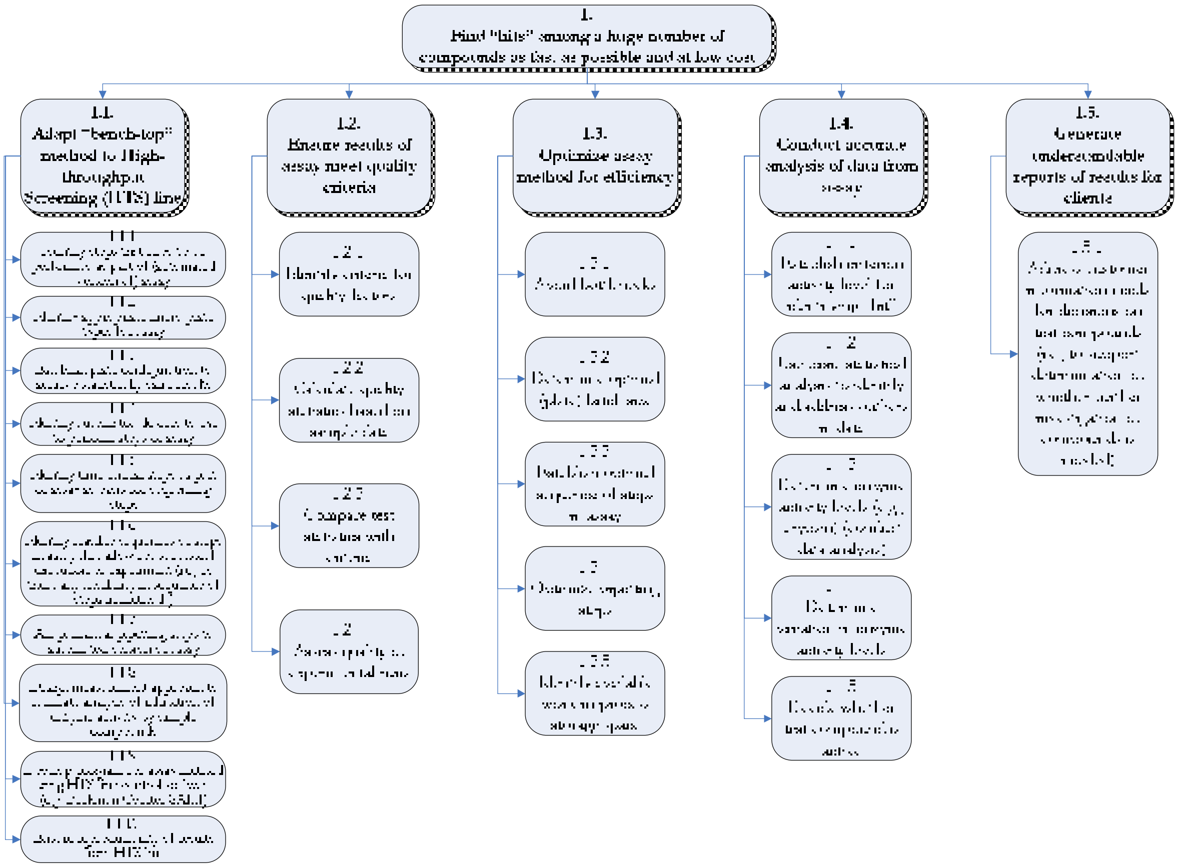

Figure 3. High-level goals as part of a HTS GDTA (Kaber et al., 2006).

In the study by Usher and Kaber (2000), a structured example was provided for applying GDTA to develop interface guidelines aimed at supporting human operator process strategy-development and decision-making. Design guidelines for supporting SA through system displays, based on a model of how system operators, gain, maintain and in some cases lose SA, provided the basis for transforming SA requirements into interface features. Recently, studies have also addressed the potential of GDTA for identifying specific SA requirements for individuals as a basis for SA training courses (Endsley & Robertson, 2000a, 2000b). Two ways for identifying these requirements have been presented, including: (1) examining what ways SA errors occur, and (2) studying the ways in which operators successfully develop and maintain SA (Endsley & Robertson, 2000a). Unfortunately, this work has not specified how SA requirements can be directly translated into training design.

In order to translate SA requirements into training program content, underlying factors driving requirements for task performance need to be identified. These factors include automation complexity and automatic versus controlled cognitive processing. Usher and Kaber (2000) indicated there are a number of critical issues with regard to how complex automation systems, like those found in HTS, can affect SA, which need to be understood. Complex automation systems with too many features make it difficult for a person to develop an accurate mental model of how the system works. By identifying the knowledge requirements for a training program, operators can be instructed on how to develop key components of mental models for HTS system operation, such as automated subsystems, the functions of these subsystems, and the projection of future actions on the subsystems. This in turn, would lead to a better understanding of the system features and how it works and to the development of more robust schemata.

Shebilske, Goettl and Garland (2000) indicate that automatic and controlled cognitive processing have a major impact on how changes in an operator's mental model occurs. The authors use Rasmussen's (1985) skill, rule, and knowledge framework for presenting the progression of a mental model from novice to expert performance and how the transformation is related to either automatic or controlled processing. They indicated that a situation model is required to represent both the internal knowledge of the operator and the contextual knowledge of the task. By identifying the information requirements of the HTS operator, training programs can be designed to organize information around goals and make critical cues for schema activation salient

Consequently, the use of the GDTA models of HTS processes may provide a method for identifying the skills required to use automated systems in terms of SA requirements, and then link such SA skills to the appropriate training techniques. It is also important to consider mediating factors like automation design and cognitive skill level in this type of analysis. Since the GDTA model does not make reference to existing automated systems or software, another CTA method is needed to represent the purpose and function of the software and devices of the HTS system.

Resource Analysis Through Abstraction Hierarchy (AH) Models

Abstraction hierarchy (AH) modeling is a representation framework used to describe human-machine interaction through a hierarchy of the functional relationships of a complex working environment in an event-independent manner in order to inform operators of approaches to recovery from unanticipated error conditions (Bisantz & Vicente, 1994). AH modeling has historically been used in complex work domain analyses (e.g. Rasmussen, 1985). It has been found to be an effective tool for revealing how automated system processes and operator functions are facilitated through specific system components and to provide explanations of why certain components are needed to achieve human-machine system purposes. In addition, a AH of a work domain can serve as a framework for identifying the operator control tasks required to maintain adequate system operation.

AH models consist of multiple levels of abstraction (Rasmussen, 1985). At the highest level, the models define the purpose of the technology in the work domain. The lowest level of an AH model represents the physical components of a system. In between, generalized functions of the system are presented. Linkages among the levels represent how the purpose of the system is implemented through specific devices (Bisantz & Vicente, 1994). This information is elicited through structured interviews with expert process engineers to establish device and automation purposes and functions.

An AH model is typically presented using a grid of three columns and five rows (e.g. Bisantz & Vicente, 1994). Rasmussen (1985) said that the five abstraction levels and three decomposition levels represent the different aspects of an operator's dynamic world model. Through the AH, the relationships within the environment can be interpreted in the context of a mental model of the work domain. Figure 4 shows the general form of an abstraction hierarchy model. The columns (from left to right) present a part-whole decomposition of the work domain to systems, subsystems, etc. The rows (from top to bottom) present functional (abstraction) decomposition of the system from the overall purpose, through generalized functions, to the physical components supporting the functions. Means-end connections are also presented across the rows (Mazaeva & Bisantz, 2007). Rasmussen (1985) identifies two problems relating to the representation of the system to be controlled using AH modeling and the consideration of the purpose or function and equipment relationships. These include finding the information for the model and structuring the information. In terms of structuring information, the data from the system should be available in a form that matches the level of abstraction being considered by the operator. In general, a systematic representation of abstract relationships among system components and subsystems is necessary for modeling and predicting decision-making behavior of operators and potential errors. Causes of errors can be explained "bottom-up" through the levels of an AH model, while reasons for proper system functioning can be derived "top-down" from the functional purpose (Rasmussen, 1985).

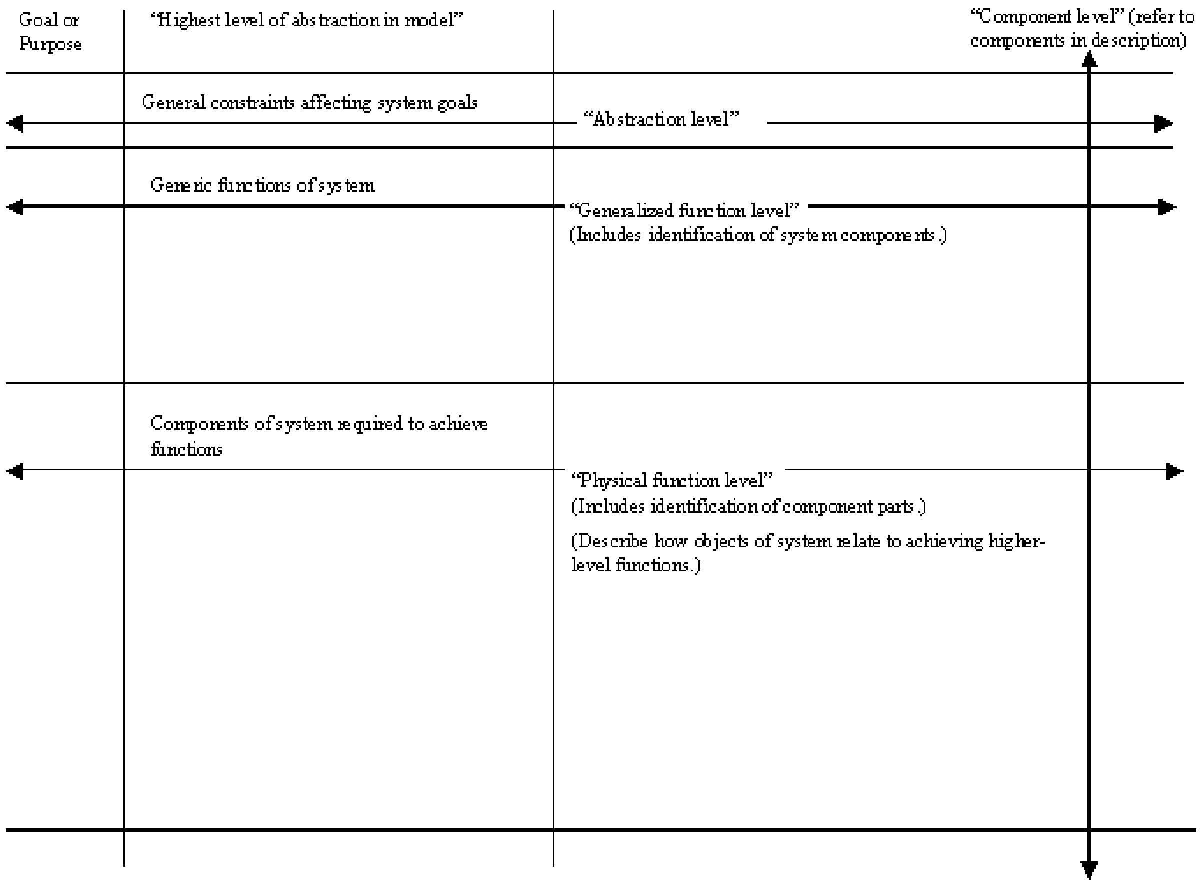

Figure 4. General form of an abstraction hierarchy model (Mazaeva & Bisantz, 2007).

One study by Bisantz and Vicente (1994) provides a concrete example of the AH, illustrating its benefits as a knowledge representation framework. A description of a simplified thermal-hydraulic process and its components at all relevant locations in the means-end/part-whole space of an AH model was provided in a series of diagrams at three levels of resolution, including component, subsystem, and system. The models were used as a basis for the development of two computerized diagnosis programs. The results of AH modeling like this can serve as a basis for developing automation technology and interfaces to help operators manage system states, when coupled with information on task strategies and operator decision-making.

Since a major concern of many training programs is that important cognitive skills are often neglected, Lintern and Naikar (1998) suggested the use of behavioral task analysis as a base from which to extend into the analysis of cognitive skills using, for example, the AH approach. Furthermore, as seen in the approach used by Schaafstal, Schraagen, and van Berlo (2000), great emphasis has been placed on the functional description of systems, similar to the AH modeling process, to develop structured training programs. It is believed that AH models can be utilized to develop system user manuals and training programs to educate operators on connections between automated control functions and software system functions, as well as interface features and options (Lintern & Naikar, 1998).

Lintern and Naikar (1998) outline an approach to extend the method of Cognitive Work Analysis (see Rasmussen, Pejtersen, & Goodstein, 1994) including AH models, to take into account the special needs of complex systems training. The AH is used to describe the context and to layout the constraints of the workspace that shape behaviors. The authors provide a simplified example of an aviation-relevant AH model, as it might be developed as part of a training needs analysis phase. Figure 5 shows how each level of the abstraction is linked to a specific use in the development of the instructional program. The labels on the right of the main figure indicate the benefits of analysis at each of the levels. As most training programs are developed from an analysis of activities used by operators to manage Purpose-Related Functions, there is a need to evaluate training programs at different levels of abstraction. Explicit identification of the Functional Purposes of a system provides high-level training objectives that emphasize adaptive and flexible action, whereas lower level abstractions identify the systems that must be represented in training devices and the data necessary for decision making (Lintern & Naikar, 1998). The next level in AH modeling, the Priorities and Values, specifies the measures of merit directly associated with the Functional Purposes. Below this, the Purpose-Related Functions can support activity analyses and identify areas for training scenario design. The two lower levels of the AH, including the physical functions and components, identify the system functionality and the appearance or feel of relevant system interfaces that are important for operators to be familiar with. Finally, this relationship between the levels of the AH and the different components of the task performance can be used to provide a basis for training performance assessment.

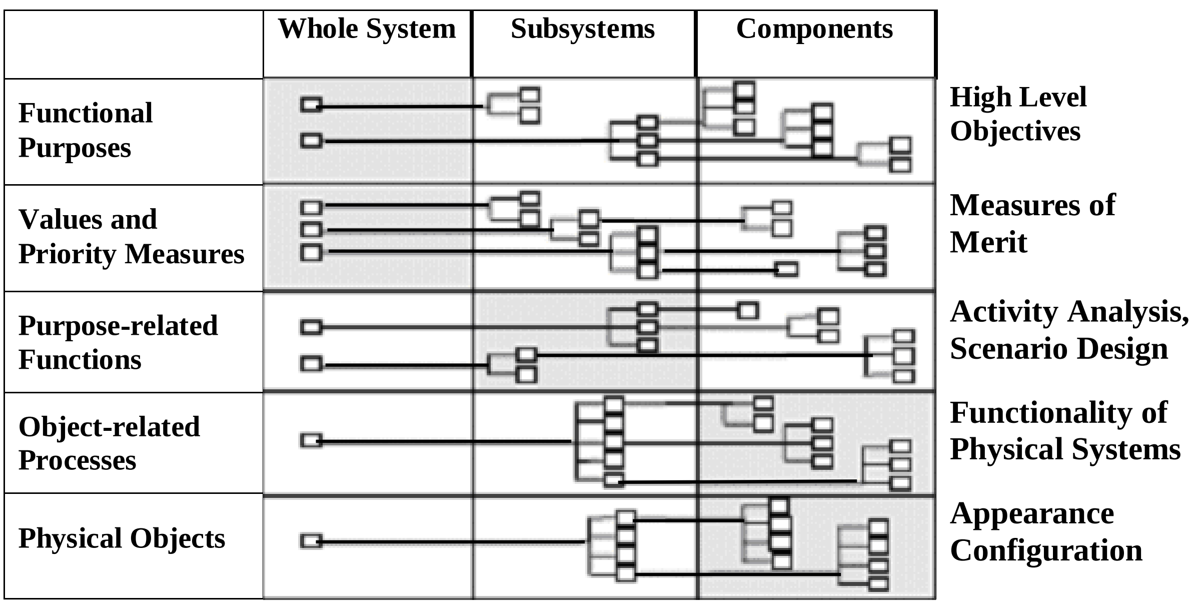

Figure 5. Links between the AH model and training program development (Lintern & Naikar, 1998).

Summary

In traditional ISD, the purpose of the task analysis is to construct a taxonomy of the tasks a trainee needs to complete, which can then be used for specifying training strategies and training parameters. It is important to note that in the GDTA, operator information requirements are established absent of consideration of the characteristics of the system interface. Therefore, operator behaviors, in terms of simple interface actions must be determined through other methods (such as AH models) with respect to general operation of complex systems, such as HTS automation. Secondly, the studies reviewed on AH modeling provide a basis and methodological suggestions for mapping CTA results into learning outcomes and training techniques. Therefore, the combination of GDTA and AH models may serve to identify the operator information requirements and goals along with required resources and system components that support these processes for task performance.

Approaches to Validation of Training Programs

There are a wide variety of views about how to approach the ISD process. Unfortunately, most practitioners treat ISD as the development of instruction and focus less on the role of the instruction within the organization or a larger educational curriculum. This may be due to the fact that training program evaluation researchers often distinguish evaluation of program utility from evaluation of program concept, design and implementation. They also distinguish between the concepts of summative and formative evaluation (Brown and Gerhardt, 2002). In general, formative evaluation is considered to be an iterative process through which revisions of instruction occur during the development of a training program, but before the actual implementation (Weston, McAlpine, & Bordonaro, 1995). Formative evaluation is intended to serve the goals of the instruction and therefore is typically designed to provide information as to whether and how well training goals are being met. In contrast, summative evaluation is defined as any effort to assess the effectiveness of a completed training program or curriculum in order to provide suggestions about use (Weston, et al.). Its purpose is to provide evaluative evidence about how well the instruction has worked. Indications of how well an instructional product or system performs can be achieved through a variety of specific formative and summative methods. Using summative methods may place more of an emphasis on how a training program fits into organizational process or curriculum design. However, such methods may be less effective than formative methods for instructional unit design because of weaker associations of actual content with feedback during training.

There are a variety of perspectives on how instructional evaluations should be structured using either formative or summative techniques. Three models most commonly considered in ISD are: Geis (1987), Dick and Carey (1996), and Weston, McAlpine, and Bordonaro (1995). Each model is identified as prototypical of a particular perspective on training evaluation. In the Geis method, two formative evaluation techniques are described, including developmental testing and expert review. The Dick and Carey Stage Model describes three stages or situations for formative evaluation: one-on-one, small group, and large group (field test). Finally, the Weston component model describes four components to be considered during formative evaluation, including participants, roles, methods, and situations. However, the total scope of their evaluation extends from the establishment of a training need through the assessment of effects of training to a determination of cost effectiveness. Interestingly, most of the models described in the ISD literature contain components encompassed by the evaluation model presented by Weston et al. Furthermore, the components in the Weston et al. model identify conditions that describe both summative and formative evaluation, but could all be described as part of a formative evaluation methodology. Therefore, the extent to which a specific evaluation method describes the components of the model presented by Weston et al., can be used as a basis for determining whether the method can effectively asses if a particular training program achieves a set of target goals.

The model by Weston, et al. (1995) was based on the review of 11 representative instructional design and formative evaluation texts to compare how formative evaluation was described, to reveal assumptions being made about the process, and to ensure the new model provided a framework and common language for understanding formative evaluation of training programs. The authors presented a model for what they called formative evaluation consisting of two stages: data collection and revision. Each of these stages consists of the four components identified above: participants, roles, methods, and situations. The first component, participants, focuses on the intrinsic knowledge that individuals bring to the training task. Roles, focuses on the tasks that are given to participants during formative evaluation of training and are categorized as evaluator, learner, critic, and reviser. The methods are defined as the procedures, techniques, and instruments used in formative evaluation. Finally, situations refer to the context in which the formative evaluation activity occurs. The analysis by Weston et al. affirmed that the model and its components encompassed various ways in which the many aspects of evaluation were described in the literature and revealed the extent to which tacit assumptions were being made about the evaluation process. Consequently, the authors suggested that methods and situations should be the components to consider first when designing a formative evaluation strategy for training systems, but that they need to be intentionally selected to coincide with goals, participants, and roles.

As part of the Weston et al. framework, two distinct processes were identified through the ISD literature to describe how the situations, methods, and instruments for training are selected including: expert review and learner verification and review (LVR). These processes can also be used to categorize the participants and roles in training. The Geis model also mentioned above addresses the uses, advantages, and disadvantages of expert reviews compared to developmental testing or LVR (Geis, 1987). Developmental testing involves naive learners reviewing learning materials at a few discrete points in the training development process. The number of participants and the quality of data may limit the situations and methods of evaluation that can be used. In the Geis model, the author also indicates a differentiation between developmental testing and LVR. The two approaches to developmental testing provided by Geis include clinical and test-focused. The clinical strategy involves intensive, one-to-one interactions between evaluator or trainee and developer. The test-focused method imitates classroom instruction with the trainee learning the material and demonstrating some degree of achievement on an objective post-test. LVR involves a continuing cycle of evaluation and editing of the instructional material during the lifetime of its use, resulting in continuously adapting situations, methods, and instruments to be used during the formative evaluation process. Therefore, the LVR process is one in which the role of the trainer and trainee have to be considered carefully to understand the results that may be expected.

The second process, concerning the various kinds of experts and the input expected from experts, is also important to defining methods for training. The role of the subject matter expert (SME) is to supply the content for instruction (while the designer transforms the content into instruction) and they typically enter the training design process early when advice is being sought on such matters. The different types of SMEs can provide information on the content of instruction or the representational accuracy of the knowledge covered. A study by Kandaswamy, Stolovitch, and Thiagarajan (1976) investigated the cost-effectiveness of two major methods of LVR often used in the field to determine the differential effectiveness of revisions made by different types of experts. The findings of this study indicate that individual differences among SMEs are reflected in the effects of their suggestions for revisions of training, which has implications for the selection of evaluators for specific situations. Therefore, careful selection of SMEs as the participants in evaluation can be an effective way to control the quality of information on the analysis of the effects of the instruction on learning outcomes and evaluation of the training content.

In designing instrumentation for gathering information from the evaluation population, there is a need to consider the design phase, the situation, and the nature of the information being gathered. Therefore, the next component to consider within the framework provided by Weston et al. (1995), are situations. The choice of situations relates to the nature of the information received from the evaluation in terms of the reliability, breadth, and depth or extent of the problems identified. The Dick and Carey Stage Model, mentioned above describes the three situations of formative evaluation as one-to-one, small group, and field trial situations. Each situation is described in terms of the criteria, learner selection, data collection, procedures, assessments and questionnaires, learning time, data interpretation, and outcomes. The three situations focus on gathering information and data about learner performance and attitudes toward the instruction. In a study by Medley-Mark and Weston (1988), they evaluated two situations within a LVR process in terms of the demand they placed on the available resources and the quality and uniqueness of the information provided through feedback. The results indicated that the one-on-one situation identified the highest frequency of problems in training program design, the most detailed types of problems, and the most unique problems compared to the small group situation. Weston et al. also indicated in their review that aside from the number of participants in the evaluation, what tends to distinguish the data collection component of situations is the nature of the interaction and the quality of data that emerges. Overall, there is more attention in the literature to data-collection situations since they relate to the nature of the feedback collected as part of the evaluation process. Therefore, based on the literature, a one-on-one situation with SMEs as evaluators has the best chance of providing information on how well an instructional product or training system performs.

Finally, there are a variety of data collection tools (i.e., instruments) that can be used at the various levels of formative evaluation and the various stages in the process. Phillips (1996) indicates that there are questionnaires, attitude surveys, tests, interviews, focus groups, observations, and performance records that are available for use in evaluating training programs. Weston et al. (1995) make the point that techniques and instruments that also specify how to remediate specific failures in the training instruction process are scarce. The lack of revision techniques and instruments indicates a reliance on the instructional designer, acting as reviser, to make the critical decisions regarding the final instructional product as well as the importance of good design bases including CTA. Unfortunately, seldom is there explicit discussion of matching the choice of even simple data collection tools to the goal of the formative evaluation.

One data collection tool that can be used in the evaluation and revision of training programs is the think-aloud procedure in which a learner verbalizes every word or thought while carrying out an instructional task in order to provide data that can later be used in the revision of the instructional materials. This data-collection methodology can consist of concurrent reporting (think-aloud) in which the learner does not theorize about the task being accomplished or retrospective reporting in which the learner reflects on the experience and then makes evaluative statements. In a study by McAlpine (1987), this procedure was found to have an advantage in the rich amount of data produced but a disadvantage in the artificial and intimidating nature of the think-aloud process for the trainee. Furthermore, McAlpine suggests that this procedure is best used only when there are serious problems with instructional materials. Secondly, the most common form of evaluation instrument within the ISD framework is the questionnaire or survey. Most published evaluation research focuses on effects of particular individual differences or instructional strategies on survey outcomes within a particular ISD framework. They are often used within "front-end" task analysis to collect task selection data (Jonassen, Tessmer, & Hannum, 1999). Several performance measures that questionnaires or surveys are often used to derive in ISD include: how often a trainee performs a task, how difficult the task is, their perceptions of important information needed to perform the task, and the consequences of making errors on that task (e.g., Axtell, Pepper, Clegg, Wall, & Gardner, 2001; Reid & Parsons, 1995). Surveys or questionnaires are fast, inexpensive ways to collect user opinions and validate task information gathered from observations. However, some of the disadvantages of surveys are that they are inflexible compared to interview techniques or think-aloud, there may be a response bias in terms of the actual task versus what is reported, and they often do not capture information about the context of situations.

Finally, if the material and/or the technology being used are new to trainees, then assessing their reactions will help prevent the use of frustrating or dramatically unappealing instructional events or features later on in the instructional design. Integrating usability testing approaches into the training design process (like surveys and verbal protocols) can help instructors anticipate some of the problems their students are bound to encounter in providing learning materials for complex domains that are engaging, memorable, and easy to read and use (Mehlenbacher, 2002). Furthermore, several studies have demonstrated the use of usability surveys to determine learning effectiveness (Koohang, 2004; Mehlenbacher, 2002). Mehlenbacher provides a list of 17 heuristic questions for evaluators to consider as they design instructional programs including such factors as completeness, consistency and error support. Heuristic evaluations as compared to user-testing or model-based evaluations are more flexible, allowing for intuition and judgment and consideration of the general goal of problem solving. This research shows that the concept of usability (and heuristic evaluation) is multi-dimensional with experience expanding how users interpret measures for assessing training systems.

In conclusion, indications of how well an instructional product or system performs must draw not only on the analysis of the effects of the instruction on the learning outcomes but also the usability-related aspects that can effect learner motivation and performance. Brown and Gerhard (2002) suggest that the largest gain in training effectiveness will occur from evaluation efforts that blend a variety of evaluation tools. Unfortunately, most formative evaluation models for training outline methods and measures without suggesting simple decision rules to judge strategy choice or tool choice for assessing training effectiveness. However, several researchers (Koohang, 2004; Lohr, 2000; Mehlenbacher, 1993) have indicated that the use of usability evaluations of electronic training systems can improve the training interface to support trainee performance and prevent cognitive errors relating to the training system interface from interfering with the learning process. Furthermore, the usability heuristics identified by Mehlenbacher (2002) take into account the conventional usability dimensions as they apply to learner centered design. Therefore, the evaluation of training programs with SMEs as the evaluators in a one-on-one situation using usability surveys may identify the greatest range of problems related to training program design. Finally, regardless of the evaluation approach taken, constraints such as time, money, resources or context, which are considered in both the training development process and evaluation, can influence the effectiveness of the instruction, overall. In this respect, the evaluation methods can determine how well the cognitive skill instruction has achieved a good fit within the organizational objectives and overall training curriculum.

PROBLEM STATEMENT

There are few descriptions of systematic approaches to the translation of CTA results, such as GDTAs and AH models, into the development of training systems for complex work domains. These methods have traditionally targeted new systems design and have not been used for explicit guidance on instructional systems development (Lintern & Naikar, 1998; O'Hare, Wiggins, Williams, & Wong 1998). Furthermore, little work has been done using GDTA to, for example, categorize skill requirements in terms of different aspects of SA as a precursor to incorporating such SA skills in appropriate training techniques. Also, specific operator SA skills identified using GDTA may be categorized in terms of the devices on which operators are to be trained by using AH models. Taking an SA-oriented approach to training by using these methods in combination may serve to identify the critical concepts related to HTS, thereby reducing the training time and cost associated with assay processing and analysis. Furthermore, taking advantage of the features of each analysis approach is expected to address different components of a HTS operator training system.

The combination of CTA methods used in this work represents an expansion on the work of Lintern and Naikar (1998), in which AH modeling is used for supporting device knowledge development through training programs. This study developed a formal procedure for combined use of GDTA and AH modeling. This new procedure was then be used to prototype an electronic training application for biologists on how to run a HTS line to conduct enzyme-based assays of organic compounds for drug development. The training program was structured to present actual system activities to be controlled by a trainee. (The objective of this work, however, was not to demonstrate the effectiveness of electronic or web-based training systems.) Information requirements and automation capabilities determined using GDTA and AH modeling served as a basis for the content delivered through the training system to support SA skill development, knowledge on the functionality of various HTS system resources, and to facilitate training scenario design. Furthermore, the combination of the CTA results was used to identify training prerequisites for novices, trainee goals, sequences of training content and to establish desired learning outcomes.

It was expected that the integrated GDTA and AH modeling approach would provide a critical understanding of operator information requirements and behaviors at system interfaces. Furthermore, the CTA-based training approach was expected to significantly improve biologist knowledge of what information to look for in a lab environment for effective screening task performance, their ability to interpret the relevance of the information to specific decisions, and their ability to project future states of a screening process in order to prevent errors.

The integrated CTA methodology permitted assessment of system and process knowledge through pre- and post-training knowledge tests and a survey of SA training effectiveness. The complete training program evaluation involved: (1) a knowledge test based on previous participant training; (2) an embedded SA assessment, (3) a knowledge test based the on CTA training program; and (4) a heuristic-based usability evaluation of the training system. Ryder and Redding (1993) recommend the use of multiple evaluation techniques like this in order to obtain convergent validation on training approaches, as each method has unique advantages, disadvantages and applications. First, the biologists were given a knowledge test before the CTA-based training; a second knowledge test was administered following the computer-based instruction in order to evaluate the effectiveness of the training program in addressing training requirements and needs. Secondly, the SA global assessment technique (SAGAT) (Endsley, 1995b) was used to assess the comprehensiveness of the training program in providing knowledge on the three levels of SA (perception, comprehension, and projection). Finally, as suggested by Brown and Gerhardt (2002), a small number of biologists were used for the heuristic-based usability survey to identify problems with the training program and ways to improve the quality of instruction without extensive user testing.

METHODS

Participants

Four expert scientists from the University of Rostock (URO) in Germany were recruited to evaluate the training system program. (These experts had participated in previous interface usability studies by North Carolina State University (NCSU) but were not aware of the objective of the current training research prior to being recruited for the study). The participants ranged in age from 37 to 41 (M = 39, SD = 1.8) and three were male. One additional expert on life science automation, not included in the training participant sample, was asked to provide evaluation criteria for the knowledge test and SA assessment, based on the training program.

Previous research has found the amount of work or task experience to be critical in learning and developing knowledge, skills and abilities necessary for effective performance (Lance, Hedge, & Alley, 1989; Morrison & Brantner, 1992; Tesluk & Jacobs, 1998). An experience questionnaire was administered to participants at the outset of the study to identify differences in basic skills and experience relating to HTS systems and processes, with respect to time, frequency, and type of task skill. A scale for rating knowledge and skill domains, as described by Raymond (2001), was used to evaluate the extent of participant experience in each of the subtasks related to the HTS robotic devices, software components and data and validation procedures, as well as participant computer experience and general English language ability. Furthermore, in order to describe and assess work experience in quantitative terms, a background survey was administered to participants on organizational tenure, academic training, and previous specialty training. This information, combined with the job descriptions of the minimum requirements for scientists hired for HTS line supervision, was used to provide a complete description of the expertise of the scientists. The background questions and modified version of Raymond's questionnaire on task experience used in this study can be seen in Appendix A. All experts recruited for the study were employees of the URO and no separate compensation was provided.

Cognitive Task Analysis

Previous task modeling work was completed as part of a cognitive work analysis (CWA) on biopharmacologist planning and execution of molecular compound screening and data analysis (Kaber, Segall, Green, et al., 2006). The CWA included a GDTA of operator behavior and AH modeling of the automated control systems used by operators to manage HTS processing equipment. The combination of AH models, describing screening line devices and automation, with the results of the GDTA were used to determine whether the task and functional requirements of biopharmacologists were being met by existing automated systems. The information requirements identified through the GDTA, combined with specification of current interface action sequences, based on the AH models, were also used to identify potential usability issues with existing software control interfaces (e.g., Beckman-Coulter SAMI®) (Kaber et al., 2006). A direct comparison of the GDTA results and AH models was used to formulate interface design and automation functionality recommendations for enhancing the existing software applications used in the HTS process at URO. The remainder of this section reviews the details on this process and identifies the results of the CWA to be used as a basis for the training system development.

The first component of the work was the development of a GDTA describing biopharmacologist goals, tasks, decisions and information requirements relevant to supervisory control of a HTS line. Structured interviews were initially conducted with biopharmacologists to develop an outline of goals, tasks, etc. as described by Endsley, Bolte, and Jones (2003). Subsequently, a collection of hierarchical diagrams of the GDTA was created to promote ease of referencing by analysts and experts in verification of the goal structure. The analysis from this previous work focused on the procedures of a biopharmacologist for adapting a “bench-top” version of a screening assay to a HTS line in a state-of-the-art university laboratory. Figure 3 above presents a diagram of the overarching goal and all major sub-goals, as part of discovering compounds that may lead to drug derivative development. The complete analysis included 50 goals, 89 tasks, 201 decisions, and 231 SA requirements. The tasks, decisions, and information (SA) requirements for the specific Goal 1.1.9.1 in the GDTA of the HTS process are presented in Figure 6. In this example, the sub-goal is the application and reading of barcode labels on a microplate as part of the Trypsin-based enzyme test method for the HTS line. Two decisions must be made by the operator when integrating the bar coder in the screening process: (1) what information will be included in the label; and (2) where will the label be applied to the microplate. The information required to address these decisions includes the code that will be used on the label. To achieve the second task, that of determining the functions of the bar coder, the operator must decide whether a new barcode needs to be applied to microplates or whether an existing barcode is to be read. Finally, biopharmacologist SA requirements were developed to answer these questions. The requirements targeted the three levels of SA, perception (observation of the system and its environment), comprehension (understanding of the system and environment relative to task goals), and projection (prediction of future system and environment states) identified in Endsley's (1995) model of SA. In this case, the operator needs to know whether a barcode is already present on the microplates (from the manufacturer or client) and what step is to follow bar coding in the assay process. To facilitate data collection (using the microplate reader), for example, it is first necessary to record the content of the barcode label.

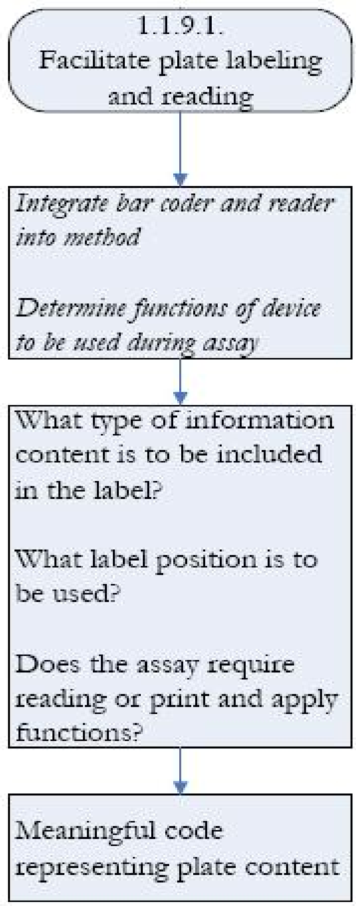

Figure 6. GDTA Diagram

As mentioned, the previous research also developed AH models for all automated devices integrated in the HTS line at URO, including the bar code print and apply device, automated pipetting robot (Biomek2000®), incubator, ORCA (material transport robot), and automated microplate reader. In addition, AH models were created for all proprietary software and action/configuration dialogs, as part of the PCS software that allowed for specific device configuration and manipulation. Related to this, the bar coder and incubator equipment have no proprietary control software. Therefore, AH models were created for the control software of the pipetting device and microplate reader, and for the PCS action/configuration dialogs for the bar code device, incubator, microplate reader, and pipetting device. The AH models on the equipment contain a total of 44 (M = 12) means-ends relationships and the AH models of the control software contain a total of 29 (M = 4) means-ends relationships.

The AH model for the bar code printer and reader is presented in Figure 7. The format of the diagram is based on that used by Mazaeva and Bisantz (2003). Following the links from the top of the diagram to the bottom, one can see how the functions of microplate labeling and reading are implemented by the bar coder components. Following the links from the bottom to the top of the diagram, one can see why the various subsystems or components, as part of the bar coder (e.g., the printer and the label paper feeder) are necessary for the specific functions of microplate labeling. At the highest level of the model, the purpose of the equipment is identified (upper-left corner of the grid); that is, to assign identifications to plates and recognize plate labels during the assay process. Directly below this level, the general constraints affecting the goal or purpose of the device (i.e., any constraining functions) are identified. For the bar code device, the constraints to plate identification include labeling and reading. Below this level, the generic functions for the device are identified, including the process of system initialization, the process of printing, the process of applying bar codes, and the process of reading bar codes. At the same generalized function level in the model, these generic processes are broken down into component processes (see across the same row of the model). The next lower level in the model is the physical component and function level. Here the subsystems required to complete the printing, applying and reading functions are identified. At the same physical function level in the model, these subsystems are broken down into components (see the same row of the model). The level of detail of the model is limited based on the expert and analyst determination of what component knowledge may be critical for operators to understand the equipment functions and to be able to diagnose faults, etc.

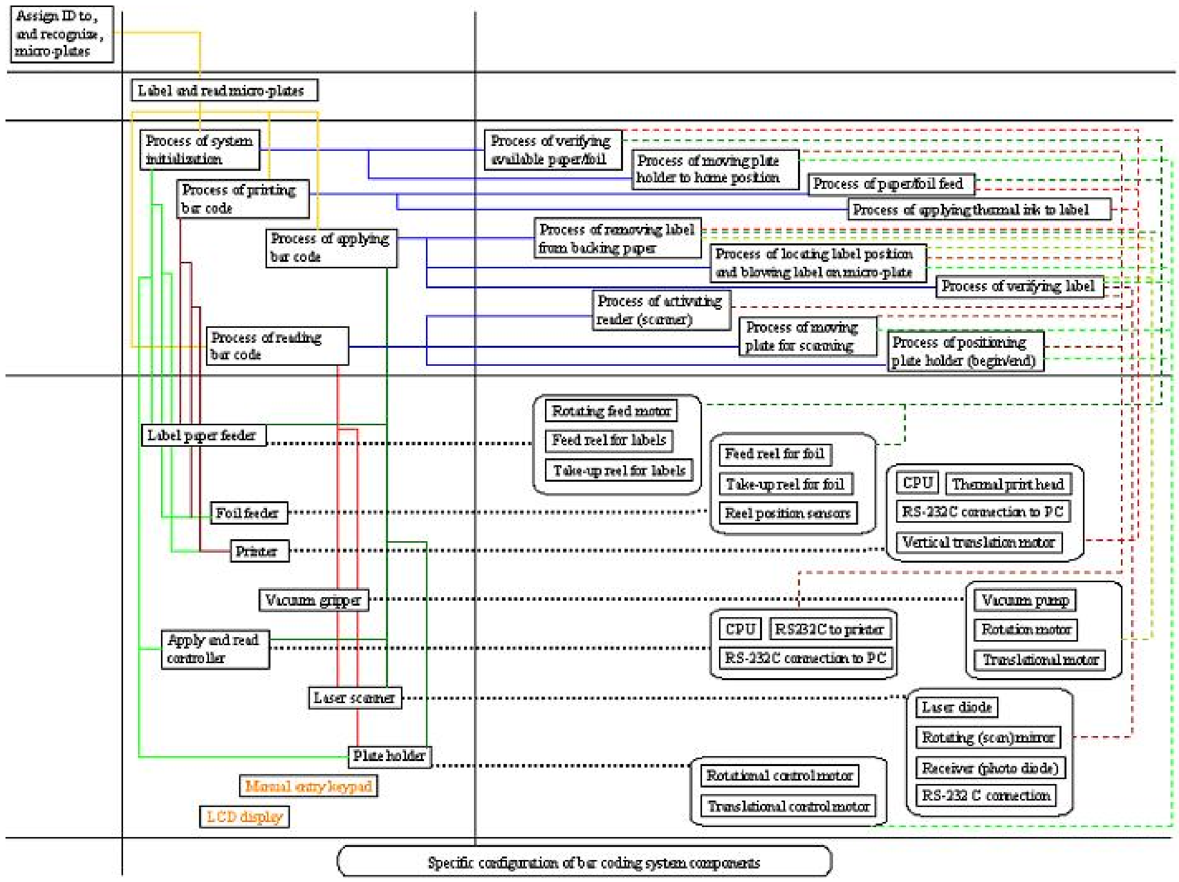

Figure 7. AH model for barcode device.

Once the GDTA and AH models were complete, they were compared in order to relate biopharmacologist goal structures and critical decisions to the purpose of the automated systems on the HTS line as well as their functions and components. More specifically, Kaber et al. (2006) used the AH models for defining the procedures by which operators would accomplish certain tasks with existing software interfaces. The steps in the procedures and interface displays were then compared to the information requirements of biochemists for the same tasks, based on the GDTA. This comparison of the outcomes of the modeling techniques produced lists of design recommendations to enhance interface and automation development. The recommendations were organized according to Nielsen's

(1993) usability framework and the framework of types of automation proposed by Parasuraman et al. (2000). In Figure 8, an example is provided of the comparison of the content of the GDTA for the goal of facilitating micro-plate labeling and reading to the interface action list for use of the bar coder action/configuration dialog, based on the AH model. To assist biopharmacologists in their decision-making, it was recommended that the software suggest to the user a default label configuration for printing and applying a new barcode, based on previously defined and stored label configurations for enzyme-based screening tests. Similar recommendations were formulated for all other goals in the GDTA that pertained to the use of software or devices, as part of the automated enzyme-based assay of compounds.

Although the research by Kaber et al. (2006) was useful from a process interface design perspective, they did not use the combination of CTA results for training program development. In the present research, results from GDTA and AH modeling of planning, control, and analysis tasks with automated screening lines was applied to the development of a training program for HTS lab operators. The integration of the components of the GDTA and AH model that were used to design the content for the CTA-based training program can be seen in Figure 9. For example, the decisions under each sub-goal in the GDTA were combined with generic functions of the system identified in the AH model to develop the training content on each task. Beyond the outcomes of this approach (identified earlier), the AH models provided information with regard to the specific device and software components supporting a specific task goal, as identified in the GDTA, and allowed for identification of the non real-time content of a part-task simulation (e.g., device diagrams and explanations).

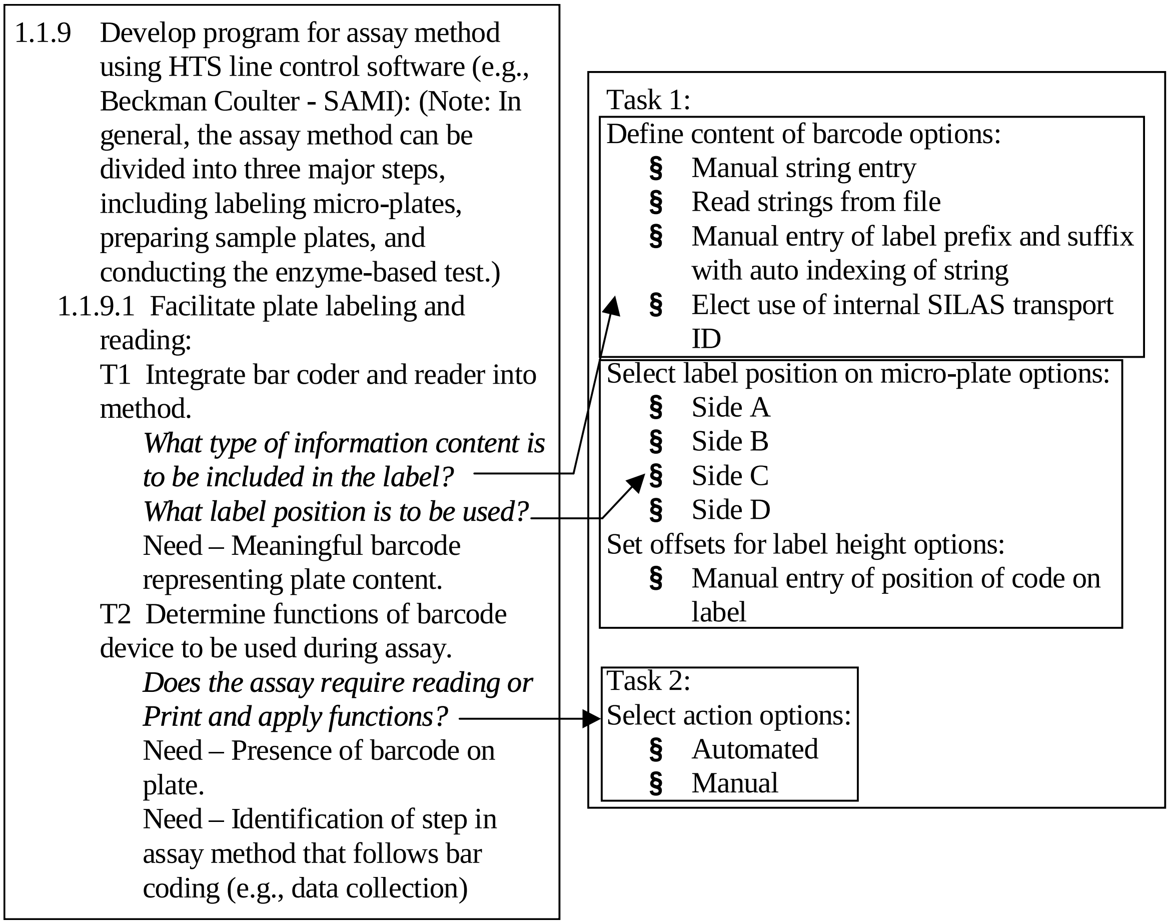

Figure 8. Comparison of GDTA and AH models for interface design.

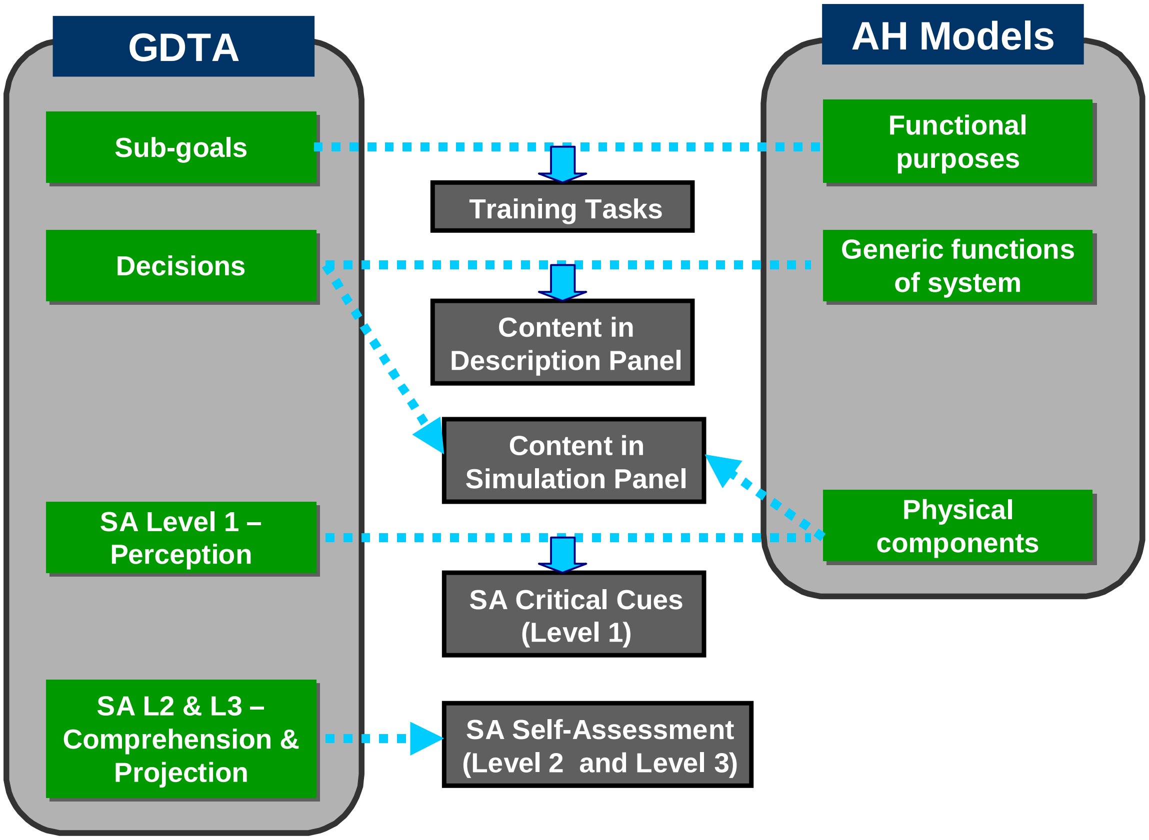

Figure 9. Integrated CTA methodologies for training program design.

Training System Prototyping

Interface Design

The new training program provided non real-time, part-task training by using part- and whole-task simulations. The program interface was arranged in four panels, each of which provided information pertaining to the task to support trainee development of the three levels of SA. The first two panels included a text description of the status of equipment and processes at a given point in a HTS task sequence and a part-task simulation of the process (which was also be used to show previous and subsequent points in the task sequence). The remaining two panels included a list of SA requirements, supporting development of level 1 SA (perception) and a set of self-assessment questions intended to promote operator understanding and projection of the future states of the process (level 2 and level 3 SA). The training prerequisites for HTS system operation were the basis for the content in the critical cue and embedded self-assessment panels of the interface. Immediate feedback was presented in the embedded self-assessment to provide operators with knowledge of results. Figure 9 shows the location and descriptions of the content of the four panels comprising the prototype training system interface. The specific design and content of each of the panels is discussed in more detail below.

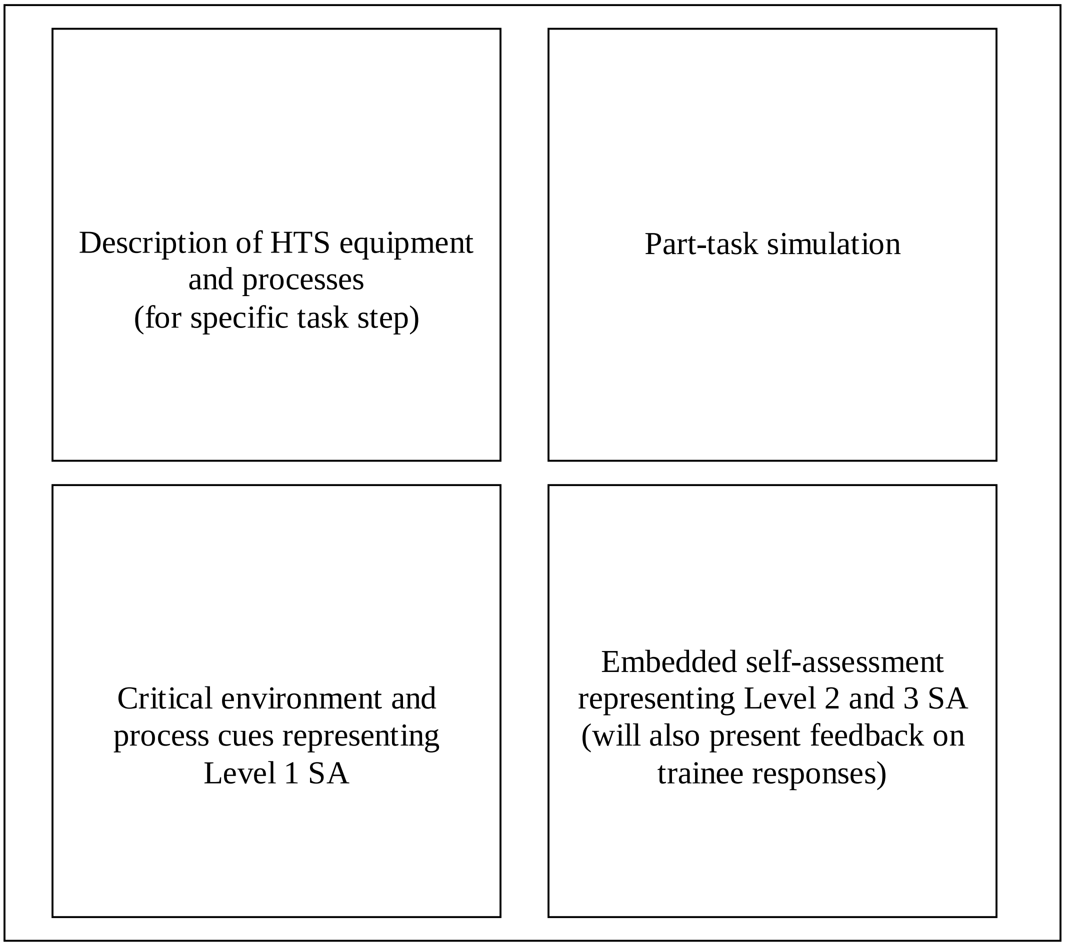

Figure 9. Representation of the four panels and information presented in the prototype training system.

The CTA-based training program was compared to a standard task analytic-based training program on the optimization of the assay method. This training interface was based on the standard format of technical training programs, in which each training screen contains the task objective and detailed information relating to the objective. A semi-structured interview was conducted with a biopharmacologist to determine the sequence of task objectives in HTS processing and the detailed information relating to each objective for assay optimization, as described by Jonassen, Tessmer, and Hannum (1999).

Task and Process-Oriented Approaches to Training and Task Sequencing

The sequence of the training tasks in the CTA-based program was determined from the breakdown of goals and sub-goals in the GDTA for planning, controlling, and analyzing the HTS process. The training system presented the tasks pertaining to the first three steps in the sequence shown in Table 1. These three steps were chosen as the focus of this work, as they require biochemist use of interactive software components to facilitate HTS processes. (This research is aimed at determining the effectiveness of a CTA-based training program specifically for improving human-automation interaction in life science processes.)

Table 1. Decomposition of HTS training tasks presented by the training system.

Step	**Subtask**
1.	Plan and design experiment components and sequence
2.	Program pipetting robot and plate reader
3.	Program method for labeling micro-plates, preparing sample micro-plates, and preparing and analyzing test micro-plates
4.	Test and validate program
5.	Ensure assay results meet quality criteria
6.	Optimize methods as necessary; correct pilot run errors
7.	Monitoring assay run
8.	Analyze data generated during assay run
9.	Generate client reports

In general, education and training programs often follow task-oriented and not process-oriented curricula. However, current training theory indicates that while it is important for students to be given an instructional context in which to learn, they also need to understand how processes work together (Alessi & Trollip, 2001). With task-oriented training programs, little attention is paid to the overall system process (i.e., how to go about solving system problems), either explicitly or implicitly. Process-oriented training, on the other hand, provides information about the conditions and constraints surrounding a topic (and not just the isolated facts) by representing what the process does, the conditions to perform the activities and the purposes and goals of the activities.

Another problem with a task-oriented approach is that learning is often contextualized, meaning knowledge or skills learned in a particular context are easily repeated by learners as long as they are in that context, but are inaccessible outside the context. This creates a situation in which those taught using a task-oriented approach to systems training tend to focus only on and understand a limited function set within the system. However, process-oriented approaches combine awareness of the process situation, the functional or task context and theoretical knowledge of the task. With process-oriented approaches, it is possible to measure how effectively knowledge, skills, or information transfer from one situation to another as well as how efficient the initial learning experience is with respect to the transfer.

Finally, task-oriented training programs often only represent the development process as a sequence of phases without a rationale justifying the performance of activities. Instead, process-oriented approaches to system training present the "right" tasks at the "right" time to support the goals of the system along with the resources needed to perform these tasks. Consequently, the presentation of the HTS training tasks will be based on a process-oriented model.

Detailed CTA-based Training Interface Design

HTS Process Description Panel. The first panel, in the new training system interface contains an outline of the detailed information related to the current task being trained. This is also presented by an audio file within the training system. This panel presents information associated with each level of Gagne's (1992) classification of learning. Verbal information on the essential features of the system, and conditional or propositional knowledge relevant to the control skill being trained for the current subtask, appears in this panel, including HTS devices and software components necessary for the task step. Therefore, the first component of each process description panel is to highlight information on any specific devices and software components that are used in the task. This information is followed by instances or examples of system performance and control skills relevant to a Trypsin inhibition test assay on a sample HTS line. The essential features of the subtask involving specific HTS devices are drawn from the operator information requirements identified in the GDTA. The GDTA was also used for information on specific operator SA skills to support system state understanding. These SA skills are associated with the various HTS devices for which the system provides training, based on the AH models. The device and software components described in the AH models, related to operator information requirements for the subtasks being trained, provide the basis for presentation of rules governing system control. Figure 10 presents an example of the process description panel for the configuration of the barcode device content found in the second task of step 3 in the training program.

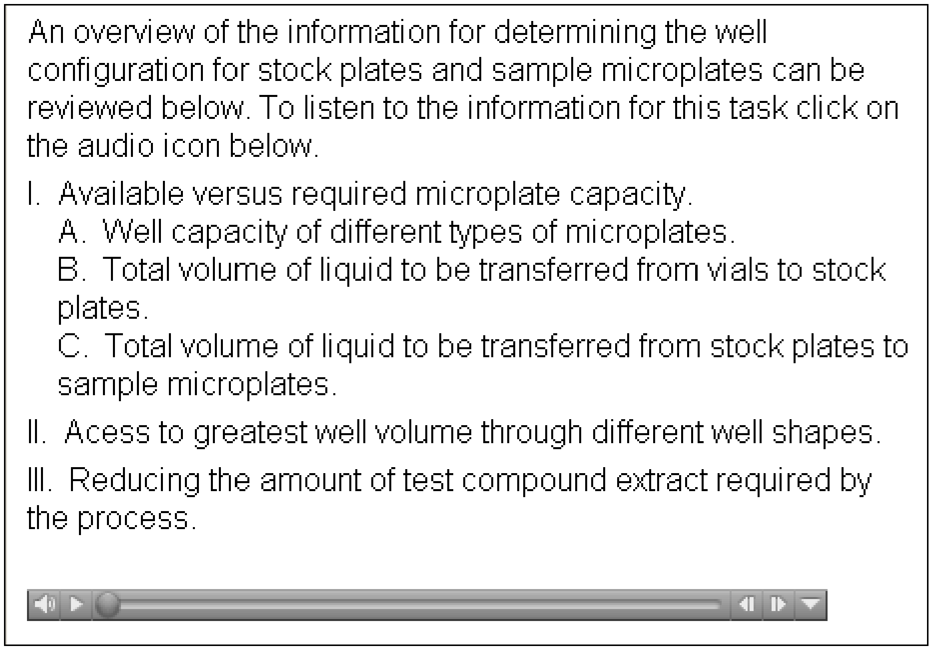

Figure 10. Process description panel.

Simulation Panel. The second panel of the training system interface contains a part-task simulation showing the information, devices and software components identified in the process description panel based on the step of the process being trained. This panel provides a non-real time event-based simulation of the process at the same point in the task sequence as the task process described in the first panel. The device and software components identified from the AH model related to the current sub-task are presented as photographs to support perception (level 1 SA) of the HTS components. Each visual on the current task process is related to both previous and subsequent points in the task sequence to support trainee understanding (level 2 SA) of the overall HTS process. That is, trainees should be able to relate the current task goals to the process states. Figure 11 shows an example of the part-task simulation images for configuring barcode content in the SAMI® software as part of the Trypsin test method for a HTS line found in task two of step 3 in the training program.

In this panel, a series of screens showing the operator the step-by-step procedures for the given task (i.e., barcoder configuration) are explained and demonstrated starting with opening the configuration dialog. The full set of screens for this task can be seen in Figures 18 through 23 in Appendix B.

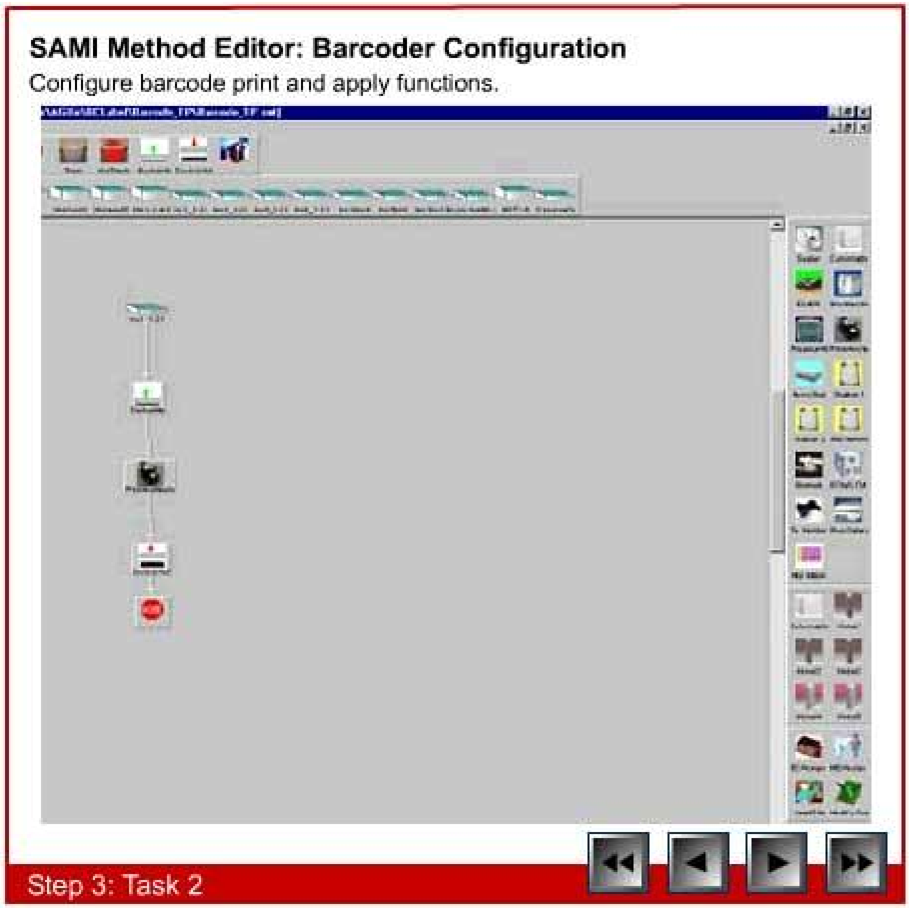

Figure 11. Simulation panel.

Critical Cues Panel. The third panel in the training system interface contains a list of the operator perceptual requirements necessary to develop level 1 SA on the subtask being trained. The list of critical cues is related to the content of the simulation panel with identifiers collocated in the simulation visuals themselves. The operator information needs and decisions related to the sub-task, based on the GDTA model, were used to identify and develop the content of this panel. Figure 12 presents an example of the device components and software knowledge necessary for determining the location of the microplate barcode within the SAMI® software, as part of the Trypsin test method for the HTS line found in the second task of step 3.

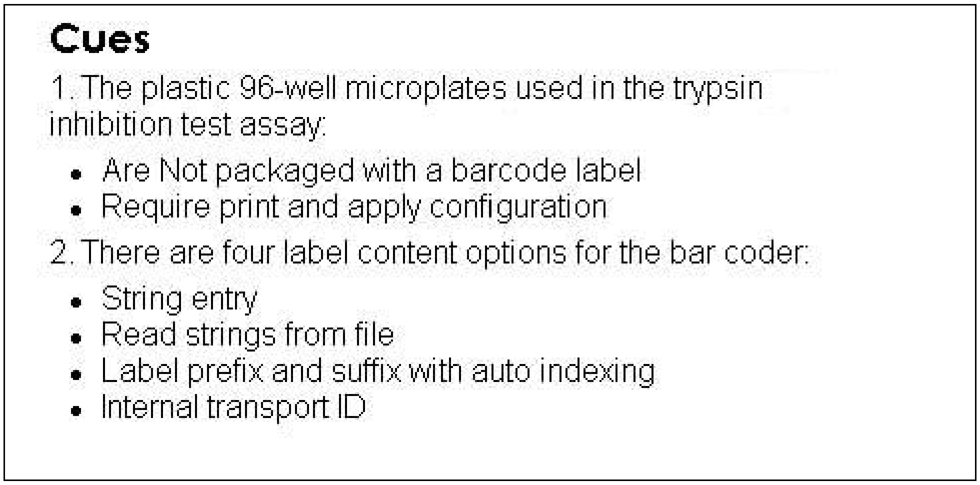

Figure 12. Critical cues panel.

Embedded Self-Assessment. The fourth panel of the trainer interface contains a set of knowledge-assessment questions towards promoting operator understanding and projection of future states of the process (level 2 and level 3 SA). The questions are based on the task decision-making requirements identified in the GDTA. The questions relate to each part-task presented in the training program. Immediate feedback is delivered on the embedded process questions to provide operators with knowledge of results. Figure 13 presents an example set of questions for the application and reading of microplate barcode labels, as part of the Trypsin test method for the HTS line, found in the second task of step 3.

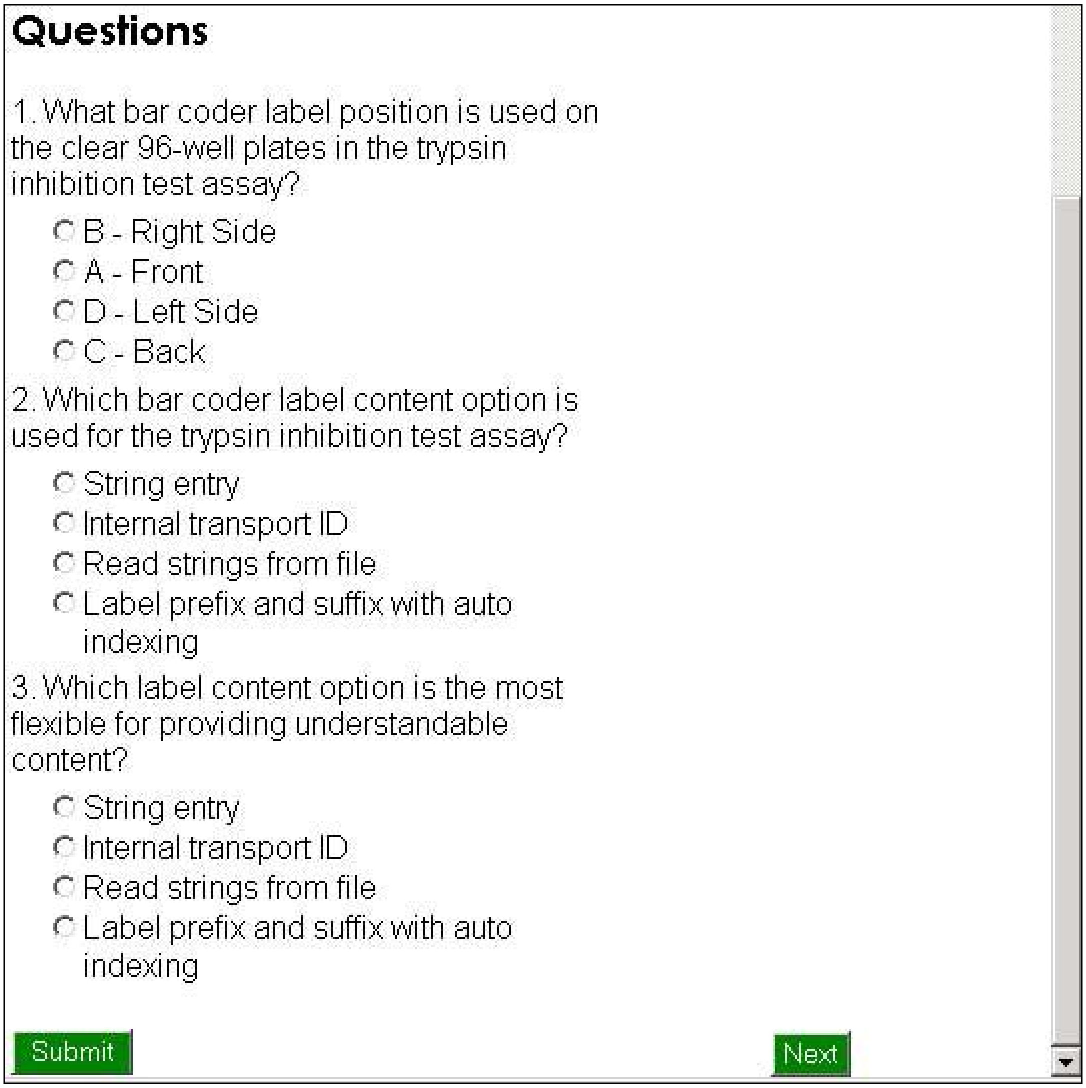

Figure 13. Embedded self-assessment panel.

All of the panels are combined into a single screen for each task. The full screen for the task of determining the functions of the barcode device to be used during the assay as part of Step 3 can be found in Appendix B.

Standard Interface Content

A standard training system interface based on the traditional task analysis approach was also developed for comparison with the CTA-based training system design. Since generic descriptions of task analytic methods in many ISD models usually involved a procedural analysis such as HTA, a semi-structured interview with an expert HTS operator was used. Furthermore, since, traditional task analytic methods were performed, only information describing the goals, sub-task performed for each goal, and the sequence of how operators perform a sub-task were used in developing the traditional training program design. Traditional task analysis methods do not include SA requirements, so the information only included the sub-task information necessary for performing the procedural steps for the goal covered by each screen. The top of the screen presented the task sub-task objective for each point in the assay optimization process. This was followed by a bulleted list of information about the equipment or environment related to process covered by the current objective. This included images of devices or process steps to illustrate the task information. The full screen for the task related to optimizing the sequence of steps within the process can be found in Figure 14.

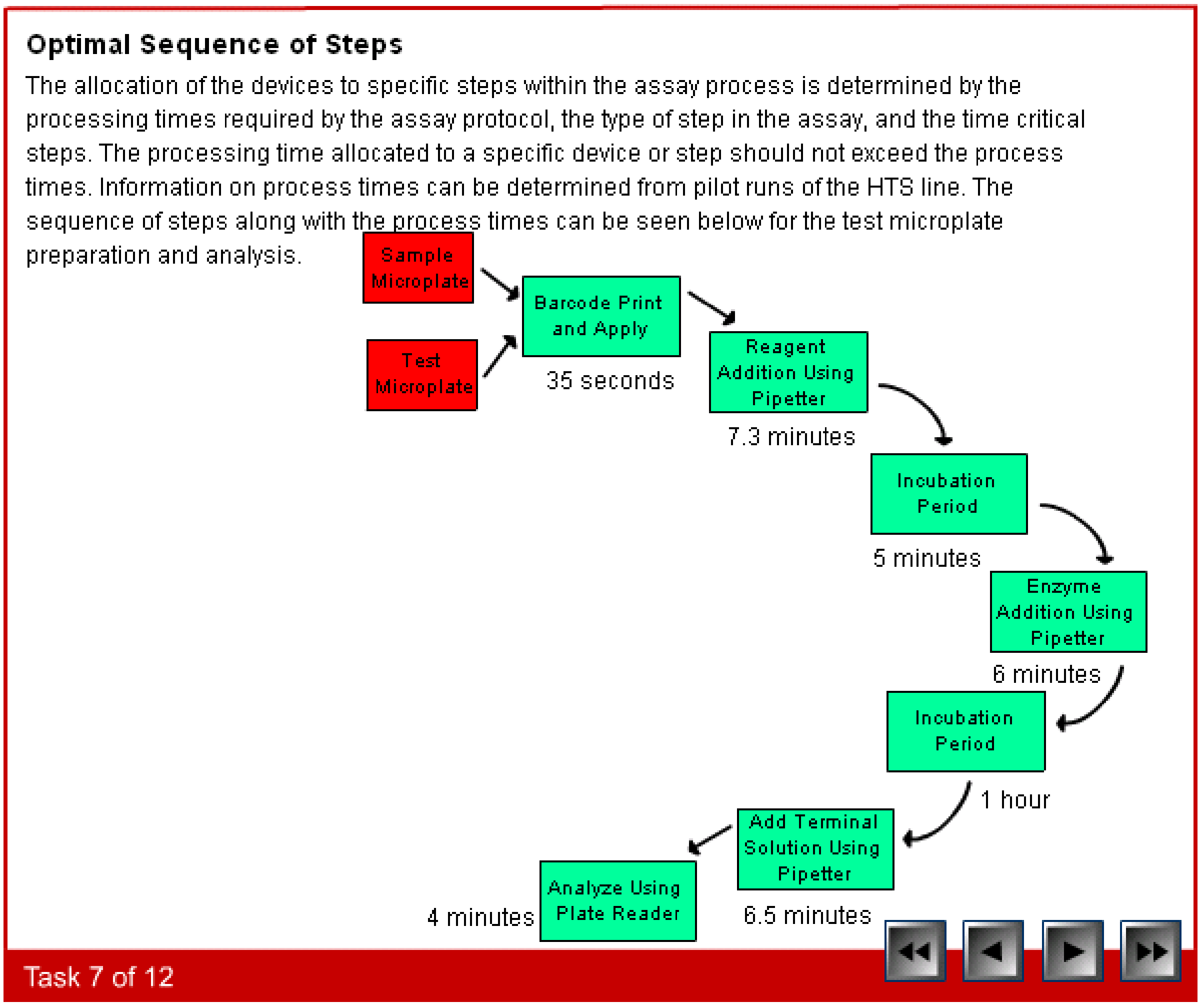

Figure 14. Task Objective 7 screen for the standard training program.

Usability Issues

A training program should provide the “right” information content at the “right” time, help learners master needed knowledge and skills, and do so in a manner motivating to learners to apply their knowledge to improve individual and organizational performance (Koohang, 2004; Molenda, Pershing, & Reigeluth, 1996). The instructional interface design process (described above) addresses the basic components of the conventional definition of usability and it integrates formative evaluation of trainee knowledge. Usability can be considered a property of a learning environment (training system interface) in which users are supported as transparently as possible (i.e., the features of the system interface are transparent) in the accomplishment of their learning goals.

While few instructional systems design models mention development of the instructional interface as a unique element (Lohr, 2000), an instructional interface is especially effective when the learner is able to focus on information content rather than focusing on how to access the content. There is a tendency for system designs to concentrate on user objectives rather than the interface tasks that may be required by such systems to achieve learning. The practices used to ensure learnability or ease of use of a computer-based training system should support mastery of the training content. This can be accomplished through a process called Learner-Centered Design (LCD) (Soloway, Jackson, Klein, Quintana, & Reed, et al., 1996), developed to address the usability needs of the trainees within a training program. Similar to User Centered Design (UCD), LCD focuses on the tasks and goals of learners. In LCD, the gulf of expertise between the learner and the learning domain must be considered. The emphasis, while designing learner-centered systems, is on the learner’s competence and proficiency in specific areas of professional knowledge, skills and understanding, and the need to bridge any gap between such competence and learning goals through usable training system design. The LCD process provides a framework for training systems that is more detailed than others and is particularly well-suited to developing CTA-based training programs. The LCD process provides guidance on the basic functions of instructional information presentation and information practice that are represented by two of the panels in the CTA-based training program.

To prepare learning material in the sense of LCD, Lohr (2000) proposed a set of three design steps based on the UCD approach: (1) understanding the users, (2) multimedia application design, and (3) usability inspection. As discussed previously, the GDTA and AH models support detailed identification of the information requirements and process resources for operators of complex systems in the performance of HTS functions and tasks. These results provide a basis for defining appropriate content, the sequencing of content, and the categorization of the skills required to use HTS systems for designing the training program.

Successful training application design requires multimedia features that enhance motivation, encoding and retention of the knowledge, as well as the use of knowledge. Multimedia training is a type of computer-based training that uses two or more media, including text, graphics, animation, audio (sound/music), and video. Meyer and Moreno (2002) present a set of five design principles for the development of multimedia learning systems. This work is based on a combination of cognitive theory of multimedia learning, which draws on dual coding theory, cognitive load theory and constructivist learning theories. The design principles include: the use of narration and animation together, the presentation of narration and animation simultaneously, the elimination of unneeded words and sounds, the presentation of words as narration rather than as on-screen text, and the presentation of narration and animation without on-screen text. Multimedia features based on these principles, which support the various cognitive processes, are considered more likely to lead to meaningful learning than those that inhibit processes. Meyer and Moreno's work suggested that any training program designed to support user motivation, encoding and retention should do so through effective and efficient presentation of the information with multimedia features. Consequently, the training system presented in this research includes the use of multimedia animation and the use of narration as text. Step-by-step simulations of each task are presented to support user motivation, encoding and retention.

Usability in LCD depends on the course content, structure and interactivity. This means that the tools, as well as the kind of interaction provided, must be aimed at supporting the learner in the specific tasks, rather than being a mere exercise of applying multimedia technology. Therefore, usability evaluation should also address measures of learning through interactivity, such as whether or not the learner recognizes and accesses instructional elements as intended by the designer of the environment, and not just measures of information salience via multiple modalities, etc.

Based on the conventional usability dimensions of effectiveness, efficiency and satisfaction (Wixon & Wilson, 1997), a learner can be provided with a training program that is comfortable to use and be satisfied with the learning process overall. Effectiveness means the learner can correctly interpret the functions of an instructional interface, or an instructional interface performs functions according to the learner's expectations (Lohr, 2000). This is related to assessing usability of the system based on LCD in terms of learning behaviors and outcomes. With respect to efficiency, a learner should experience minimal frustration interpreting an instructional interface function, or the learner should experience minimal obstacles in using instructional interface elements. This is generally a more superficial usability goal and involves the design of buttons, labels or menus that facilitate learner interaction and engagement with instructional content. The objective of efficiency can be accomplished by identifying the possible actions that a learner may take and devising ways to handle those actions during the design process through specific types of interface features. Finally, satisfaction is related to how comfortable the learner seems in the environment overall and their desire to learn (Lohr, 2000). For this objective, evaluation of the system design should identify the overall acceptability of the instructional interface design. By addressing these usability objectives throughout the design process, the training system should provide the trainee with the best support during training.

Procedures

The experimental training program and evaluation consisted of five phases: (1) training instructions and the background (operator experience) questionnaire; (2) the initial knowledge test; (3) the training regimen and SA assessment; (4) the usability questionnaire; and (5) the final knowledge test. This sequence of steps and the estimated times for each step can be found in Table 2. Since participants for this study were located in Germany, the researcher traveled to Rostock for face-to-face meetings with the participants and to provide detailed instructions for accessing the HTS training programs and evaluation materials. First, each participant was presented with the background questionnaire, including questions on HTS system experience, computer experience and general language skills. Once they completed these introductory steps, participants were administered the initial knowledge tests. Limited feedback was provided to the participants on the knowledge tests, including the number of correctly answered questions over the total number of questions. After all participants completed the knowledge test, the training programs were presented. A randomized within-subjects design was used for presentation of the two training programs (CTA-based training and traditional training).

The training regimen consisted of reviewing the text descriptions on the HTS equipment and processes as well as the critical cues associated with the part-task simulation for different instances of the HTS process. Participants answered the embedded SA questions addressing understanding and projection of future states of the process. Feedback was immediately followed the questions on each HTS subtask. After all tasks relating to a particular sub-goal were reviewed, an additional interface presented the SA assessment questions. This sequence was repeated for each training sub goal. The training program was followed by a heuristic-based survey on the usability of each of the ten subtasks of the training program. Lastly, following a one-week retention interval, the second knowledge test was provided. During the one-week retention interval, participants continued with their regular job tasks. This did not include exposure to the exact task information presented in either training program or information directly relevant to knowledge test questions. Participants also did not search for information on knowledge questions. At the end of the final knowledge tests, participants were debriefed on the objectives of the study.

Table 2. Overview of experimental procedure and approximate time estimates.

Step	**Time Estimate**
Instructions and experience survey	30 minutes
Initial knowledge tests	1 hour
Training program with embedded SA assessment	3 hours
Usability evaluation	30 minutes
Overall training effectiveness	5 minutes
One-week retention period	
Step	**Time Estimate**
Final knowledge tests	1 hour
Debriefing	5 minutes

Dependent Measures

Initial and Final Knowledge Tests

Two criterion referenced knowledge assessments were created to measure the skills required for both the CTA-based design for programming and control of a HTS line and the standard training system interface design for assay optimization. The initial knowledge assessment test measured biopharmacologist knowledge based on their current on-the-job training (see Appendix C). The second knowledge assessment test measured the improvement of biopharmacologist knowledge based on the CTA-based training program or the standard training program. One knowledge assessment test was constructed as a random order of the items on the other test. This randomization of the order of test items within the knowledge assessment tests reduce memory affects on participant responses, which is a particular problem associated with the reliability of the test-retest method (Thorndike, 2005; Urbina, 2004).

In general, there are criteria that all assessment instruments should follow for any effective test of training. Assessment instruments should be designed according to a clear construct definition, use appropriate test specifications and be composed of well-written items. According to Dick, Carey and Carey (2001) certain types of behavior can be tested in several different ways and should be addressed in terms of the learning domain or the objective. The assessment items included in the knowledge tests were based on the subset of the 139 goals and tasks identified in the GDTA on HTS operations that represent the first three steps of the HTS training tasks. Test items were created as multiple-choice, four answer questions. This resulted in 38 knowledge questions for the CTA-based training program and

17 knowledge questions for the standard training program, scored as correct or incorrect (again, see Appendix C). A goal or task was translated into a selected-response assessment item using the item templates described by Haladyna (1999). This process involved the following steps: (1) determine the cognitive behavior that is represented by the task; (2) identify a stem for representing the content of the item; (3) write the item stem; (4) write the correct answer; and (5) write the required number of distracters. A completed item consisted of a subset of the following constituent parts: item directions, text and graphics, item stem, correct response, and response alternatives. Figure 15 presents an example of the development of an item based on the biochemist task of determining the functions of devices to be used during an assay (Goal 1.1.9.1). Finally, many general heuristics are available for creating effective items when constructing a test. Table 3 provides seven criteria by which “good” assessment items can be constructed.

Step 1. The cognitive behavior for this task is related to Level 2 SA. **Step 2. Select a stem for evaluation by using a principle:** What is the most important factor contributing to...? **Step 3. Write the item stem:** What is the most important factor contributing to the selection of the label position for plate labeling and reading? **Step 4. Write the correct answer:** A. The presence of an existing barcode on the microplate. **Step 5. Write the distracters, up to five options:** B. The location used in the "bench top" version of the assay C. Manual entry of the content will be used for the assay. D. A data collection step occurs next in the assay method. E. Whether the microplate used in the assay can hold a barcode label.

Figure 15. Item creation for the second task under goal 1.1.9.1 using a generic item shell.

Table 3. Criteria for constructing assessment items (Osterlind, 1998).

- Must be congruent and clearly defines according to the key objective (or construct)
- Test item format should be appropriate to the goals of the test
- Base each item on a single, specific content or learning category
- Keep the specific content of items independent from one another
- Keep vocabulary congruent with the learners being tested
- Make sure that only one response is the correct response
- Avoid giving clues to the correct response (e.g., longer correct response, grammatical inconsistencies, or ridiculous options)
- Test items meet all ethical and legal concerns

Since the item template process has a tendency to produce inter-item cuing (Haladyna, 1999), it is particularly important that careful practice be used when developing the complete set of assessment items. Therefore, the full set of knowledge assessment test items were reviewed by an expert biopharmacologist before use, in order to ensure that all items met the criteria identified for "good" assessment items in Table 3. The expert reviewer was provided with the set of knowledge assessment test items and the assessment item criteria in the form of a checklist. The expert reviewer checklist was used by the additional biologist, not included in the test sample, to verify all elements of the knowledge test met the criteria defined by Osterlind (1998). Each item was evaluated as a “good” item if it successfully met all eight of the criteria. This evaluation also served to confirm that multiple answers for each question were not correct since different answers to knowledge test questions may be considered acceptable to different operators, due to individual differences in knowledge structures. The expert review checklist can be found in Appendix D. The results of this review revealed that the knowledge assessment test met the criteria for a “good” assessment for 95% of the questions and was rated at a moderate level of difficulty. The level of difficulty was considered sufficient by the expert to prevent ceiling and floor effects during knowledge assessment of HTS operators. Further detail on the expert review is provided below.

Training Program Development

The CTA-based training program prototype was developed using HTML (web pages) with embedded Javascript and Macromedia Flash applets for the SA assessment and system simulation, respectively. This web application development allowed for collection of observations on trainee learning (e.g., responses to embedded SA questions). Participants were presented with questions in the training program for each of the 19 training task segments. These questions were based on the SA requirements for each of the training tasks. Feedback on the embedded questions was provided to improve learning recall and mental model structure. Immediate, item-by-item, corrective feedback was presented within the embedded question panel by the selection of a "submit" button in the panel. The feedback was in the form of "correct" or "incorrect" with information on the correct response. The number of embedded questions completed during training was recorded and provided a measure of the percent of the training program completed and the number of higher-level SA question errors. Here, it is important to note that these questions do not represent the SAGAT methodology as described by Endsley (1995b), but serve to provide trainees with an interactive measure of knowledge construction related to the 3 levels of SA.

The traditional training program prototype was developed using HTML (web pages) with embedded Macromedia Flash applets to maintain a similar learning environment across the two training programs. Since the traditional instructional system design methods would not normally include embedded feedback or SA requirements, the design did not include collection of learner responses or SAGAT questions. Therefore, each screen only included the sub-task information necessary for performing the procedural steps for the goal covered by each screen.

SA Assessment

An adaptation of the Situation Awareness Global Assessment Technique (SAGAT) was used to assess the completeness of the training program with respect to HTS operator SA. The SAGAT allows for direct, objective assessment of operator SA by making a comparison of operator responses to knowledge questions with the ground-truth of an actual situation or simulation state. This approach is designed to address the problem of operator recall of system or environment states associated with knowledge questionnaires presented at the close of training trials or the problem of cognitive loading and potential performance decrements associated with on-line questions or real-time probes (Endsley, 1995b). Previously, Endsley (1995b) presented two studies investigating the validity and intrusiveness associated with the SAGAT in fighter piloting simulations. Results indicated that the method was not intrusive to participants during task performance and response accuracy was not reduced by memory limitations, establishing the empirical validity of this technique. Using this technique, the accuracy of operator perceptual knowledge, comprehension of environment states relative to goals and predictions of future states can be accurately assessed and related to performance. The key advantages of the SAGAT are that it provides a global assessment of SA across all three levels and diagnostic information about specific elements of operator SA. Findings have indicated that this type of measure is sensitive to changes in task factors and operator attention (Endsley, 2000). In the present experiment, SAGAT questions were presented to trainees in parallel with the training content. At random points within the training program, an additional interface was presented with a set of SA questions targeting those subtasks recently completed. These questions were based on the content of the critical-cues panel and the embedded-questions panel for each subtask.

SA questions were formulated based on the 85 information requirements identified in the GDTA (see Appendix E) associated with the first three steps in the HTS process and solicited a single response from participants. An example of a SA question related to Goal 1.1.9.1 Task 1 is as follows: “Which step in the assay method comes next, according to the "bench top" version?” The full set of SA questions used in the SA queries can be seen in Appendix E.

The results of each SAGAT query opportunity were calculated (percent correct responses) and the scores served as an indicator of biopharmacologist SA in the programming, control and analysis of an HTS process introduced by the training system. Percent correct responses to SA questions were calculated for each level of SA defined by Endsley (1995a) (Level 1, 2, and 3 SA) and an overall score was also determined. This provided a measure of the comprehensiveness of the biopharmacologists knowledge structures following the CTA-based training program in terms of perception of critical cues, comprehension of the relevance of cues to system goals and the use of cues for projecting system states.

Usability Survey

Previous research on usability in instructional design suggests that usability principles are reflected not only by the content and learning elements of a system, but also the properties or features of the system (Mehlenbacher, 2002). The expert biologists participating in this study evaluated the CTA-based training materials on 17 usability attributes: accessibility, aesthetic appeal, completeness, consistency and layout, error support and feedback, examples and case studies, functionality, navigability, organization and relevance, readability, and typographic structuring. The survey first required that the evaluator inspect the training program for violations of attributes and then list specific problems that could negatively affect usability in terms of the respective attribute. In this process, each attribute was rated as “successful” or “unsuccessful.” Only unsuccessful attributes were accompanied by lists of problems. The survey containing the 17 heuristics along with a description of each heuristic can be found in Appendix F. Interface problems were recorded and, in some cases, suggestions for correcting them were also noted. Evaluators prepared lists of problems, which were combined into one list for all subjects for each attribute. The number of violations for each attribute was totaled across evaluators as a measure of overall usability of the training interface. The tally was compared with the estimated total possible unique problems that could be identified for the system and a usability percentage was calculated. The total possible unique problems identified for the training system was estimated (assuming each of four evaluators identified a single distinct usability problem for each of the 17 heuristics) at 68 unique usability problems. The percentage of usability problems was then compared with an established usability criterion from the literature (see below). In addition to this measure, percentages of evaluators providing common comments or identifying common problems was determined. These measures are expected to confirm or refute that the training interface design did not have a negative impact on learning.

Hartson, Andre and Williges (2003) indicate that a sample size of 3 to 5 participant evaluators is sufficient to find approximately 80% of the usability problems in a system, given average individual detection rates. The authors also offer that subsequent to addressing these problems, the majority of evaluators will consider a system to be usable. This suggests that a training program design should be at least 80% successful in addressing learner centered usability principles. Virzi (1997) and Nielsen (2007) indicated that if the sample of evaluators recruited for a study extends beyond five (for example, the number of evaluators could be set to the number of potential unique problems) the likelihood of identifying the remaining 20% of usability problems increases. For the selected sample size used in this study, a successful design would be one in which the training program is found to contain less than 20% of the possible unique usability problems that could be identified by biopharmacologists.

Detailed Hypotheses

Hypotheses on CTA-based Training and Task Knowledge

In the present research, it was expected that the CTA-based training program would improve biopharmacologist knowledge structures beyond prior OTJ training as well as compared to traditional training program design. Specifically, it was hypothesized that a comparison of the results of the initial process knowledge test versus the final knowledge test (after CTA-based training) would show an improvement in biopharmacologist knowledge structures beyond OTJ (Hypothesis 1, H1). Preliminary validation of any benefit of use of the CTA-based training approach, was also expected through comparison with traditional operations training. Therefore, it was expected that HTS operators would demonstrate a greater improvement in knowledge test scores from the initial knowledge test to the final knowledge test for the CTA-based training program than for the traditional training program (H2).

Since the amount of previous task experience may be critical in learning and developing knowledge, skills and abilities necessary for effective performance, a comparison of the initial knowledge test scores for both training programs and the levels of biochemist education, OTJ training, and experience was performed. These comparisons were used to quantify the role of the CTA-based training in biochemist knowledge beyond existing experience and education. Therefore, the greater the number of years of HTS process experience, and the higher the level of education, the smaller the expected change in knowledge test scores for both training programs (H3). Furthermore, it was expected that operators with greater frequency of previous task performance and level of knowledge relating to previous task experience would have a smaller change in knowledge test scores for both training programs (H4).

Hypotheses for CTA-based Training for Situation Awareness

It was also expected that a CTA-based training program identifying the information elements of the HTS domain, related to each of the levels of SA in Endsley's (1995a) theory, would lead to a more complete understanding of the SA requirements in HTS processes for trainees as compared to OTJ training (H5). The accuracy of biologist responses to the SA questions was assessed relative to the level of performance an expert biologist would be expected to demonstrate and chance. The former criterion was set by the additional biopharmacologist not included in the test population. Finally, the amount of overall previous task experience, measured as the number of years of experience, or level of education, and the initial knowledge score for the CTA-based training program were expected to result in a linear increase in SA assessment performance for each level and overall SA (H6).

Hypotheses on Training System Usability

Since it is necessary for learners to be provided with training programs that are transparent in function while concentrating on the objectives of the training, the three design steps of Lohr's (2000) LCD approach were followed in the design of the HTS training program. By following this approach, the training system interface was expected to be considered usable by biochemists (H7). A usability questionnaire was used to identify any design problems associated with the training program interface. The percentage of usability violations out of the set of all possible unique violations that could be identified was used as a measure of overall training system usability. This measure was expected to confirm or refute that the training program interface design was usable and did not pose a negative impact on learning. Furthermore, the CTA-based training program was expected to provide learners with a more effective overall learning experience than with the standard training program (H8). An overall subjective rating of the usability of the two training programs based on the heuristic questionnaire was used to compare overall effectiveness.

Data Handling and Analysis

Since a response was required for all SA and knowledge assessment test questions, they were scored as a ratio of correct answers to possible responses. For example, the number of correctly identified information needs was used as a numerator in the SA ratio and the total number of SA questions was used as denominator. Since the responses to the questions represent a binomial variable (correct or incorrect), the distribution of this data violates parametric statistical test assumptions (particularly normality of a data set). Furthermore, any comparison of the knowledge test results or the knowledge assessment test results with the SA assessment results would violate assumptions of parametric statistical tests. Beyond this, the small user sample size also dictated that the distributions of the response measure data sets did not approximate the normal distribution, or the *t*-distribution. Therefore, distribution-free test alternatives to multiple linear regression, the independent group *t*-test, and Pearson coefficients were used for all analyses.

Analysis of CTA-based Training Effects on Task Knowledge

Correlation analyses were conducted to identify the significance of any relationships between the various response measures for both the CTA-based and traditional training system programs including: (1) the results of the change in knowledge test scores versus education level and years of experience; and (2) the results of the change in knowledge test scores broken down for each of the 10 sub-tasks being studied (identified in the GDTA diagrams) versus operator frequency of task performance, level of knowledge of task, education level, and years of experience (H3, and H4). Beyond this, correlation analyses were conducted to verify the importance of accounting for participant education and experience in knowledge test performance versus considering age. Since some of the sub-tasks were represented by three or less questions, there was no difference on initial or final knowledge test scores between participants, therefore the change in knowledge test scores from initial to final test were used for these analyses. A large positive correlation coefficient would indicate an association between the role of experience in improving knowledge assessment test scores and a large negative coefficient would indicate that greater knowledge assessment test scores were associated with less experience. The SAS PROC CORR SPEARMAN procedure was used to establish the statistical significance of the correlations of interest to the study.

Wilcoxon rank sum tests were conducted to identify the significance of any linear relationships between the various response measures identified with Spearman coefficients including: (1) the results of the initial knowledge test versus the final knowledge test for both training programs; (2) the change in knowledge test performance between the training programs; and (3) results of the knowledge tests broken down for each of the 10 subtasks being studied versus operator frequency of task performance and level of knowledge of task (H1, H2, H3 and H4). The SAS PROC NPAR1WAY WILCOXON procedure was used to establish the statistical significance of the relationships of interest to the study.

In order to look at the relationship between the results of the knowledge tests versus the experience measures including education level and years of experience, the scores for these measures were categorized into high and low education levels (a category of high education level was for operators with 20 or more years of education) and number of years experience (a category of high experience was used for operators with 10 years or more of experience). Using this categorization for experience, Wilcoxon rank sum tests were conducted in which the SAS PROC NPAR1WAY WILCOXON procedure was used to identify the significance of any linear relationships (H3).

CTA-based Training for Situation Awareness

The Wilcoxon sign rank test procedure was used to determine any differences in the performance for the three levels of SA and overall SA according to chance and according to the expert criterion of 80%, for the CTA-based training program (H5). The SAS PROC UNIVARIATE procedure was used to establish these relationships.

Furthermore, since experience was expected to influence knowledge test results as well as SA assessment performance, an analysis was performed to determine the effects of subject experience level on performance on the knowledge assessment test, and SA question scores. Therefore, correlational analyses were also conducted to identify the significance of any relationships between the three levels of SA and overall SA and the following overall experience measures: (1) number of years of experience and (2) level of education. The SAS PROC CORR SPEARMAN procedure was used to establish the statistical significance of all correlations. In order to identify differences in performance on the SA assessment due to initial knowledge and the CTA-based training program as well as the experience measures, a distribution-free multiple linear regression analysis was performed (H6). The SAS PROC GLM with PROC RANK data procedures was used to establish the statistical significance of these predictions.

Training System Usability

Finally, with respect to the usability evaluation of the training system, a detailed analysis of the percentage of usability issues identified by biologists, for each of the 17 attributes included in Melenbacher's survey, was conducted. In this analysis, the frequency of each unique problem identified during training sessions was calculated. The total number of unique usability problems that could be identified for the training system was estimated at 68 usability problems. As noted above, a successful training program design can be considered one in which no more than 20% of unique possible problems are found by evaluators (Hartson, Andre, & Williges, 2003). Therefore, if the training system design was successful in following the learner-centered usability principles, the usability evaluation should result in, at most, 17 unique usability problems (H7). A Wilcoxon rank sum test procedure was also used to identify the significance of the comparison of the overall ratings for the usability of the CTA-based and traditional training systems (H8). The SAS PROC NPAR1WAY WILCOXON procedure was used to establish the significant difference between overall ratings.

RESULTS

To ensure the knowledge assessment tests met the criteria for “good” assessment items, an expert HTS operator reviewed the questions for the CTA-based training program. The expert review resulted in 2 questions with more than one response possible, which were corrected prior to administration to participants (see Appendix C). Only 5% of all knowledge assessment test questions were considered to be somewhat “poor” assessment items. Consequently, the knowledge assessment test for the standard training program, which was developed in a manner identical to the development of the test for the CTA-based training program, was not reviewed by an expert biopharmacologist. Furthermore, to ensure the CTA-based knowledge assessment test was of a sufficient level of difficulty, a difficulty evaluation rating was performed by the same expert biopharmacologist. The overall difficulty level of the test was rated as “somewhat difficult.” Table 4 shows the percentage of questions at each difficulty level.

Table 4. Difficulty level of questions in the CTA-based training program (*n* = 38).

Difficulty Level	Questions
Extremely difficult	0%
Very difficult	8%
Somewhat difficult	39%
Marginally difficult	45%
Not difficult	8%

CTA-based Training Program and Experience Effects on Training

This study compared HTS operator knowledge structures based on the CTA-based training program with prior OTJ training and a standard non-CTA training program design. First, since previous task experience may be critical in developing operator knowledge structures, performance on the initial and final knowledge assessment tests for both training programs were correlated with two standard measures of overall experience (H3). Table 5 contains the Spearman test correlations and medians for level of education (Education) and number of years of experience (Experience) with the initial (I) and final knowledge (F) assessment test scores for the CTA-based (CTA) and traditional (TRAD) training programs.

There was evidence of a significant positive association between number of years of experience (Experience) and the final knowledge assessment test scores for CTA-based training program, $p = .05$. There was also evidence of a significant positive association between level of education (Education) and the initial knowledge assessment test scores relating to the traditional training program, $p = .05$. Correlational analyses indicated that increasing experience (number of years of experience) was associated with increasing final knowledge assessment scores for the CTA-based training program. Greater experience (level of education) was also associated with greater initial knowledge assessment scores for the traditional training program, which are expected for an initial assessment test. Finally, correlational analyses also indicated no significant association between age and level of education ($r = 0.21$), or between age and number of years of experience ($r = 0.32$), $p > .05$. Therefore, evaluation of the finer-grained variables, including education level and experience, proved to be statistically meaningful versus considering biochemist age.

Table 5. Correlations and medians for number of years experience, level of education, and knowledge assessment test scores.

Variable	Spearman rho					
	Experience	Education	CTA-I	TRAD-I	CTA-F	TRAD-F
Education	-0.83					
CTA-I	0.32	0.21				
TRAD-I	-0.63	0.95*	0.40			
CTA-F	0.95*	-0.63	0.60	-0.40		
TRAD-F	-0.83	0.89	0.21	0.74	-0.63	
Median	10	20	0.55	0.50	0.83	0.71

*p = .05.

Since there was a significant linear relation between number of years of experience and improvement on the final knowledge assessment tests, a further analysis was performed to determine if greater experience led to greater improvements in knowledge assessment scores for the CTA-based training program. A Wilcoxon rank sum test procedure indicated that there was no significant difference in change in the knowledge assessment test scores from the initial to the final test (for the CTA-based training program) based on a high or low number of years of experience (Experience), $W = 6$, $p = 0.33$. Furthermore, since there was a significant linear relation between level of education and the initial knowledge assessment tests, a further analysis was performed to determine if greater experience led to greater improvements in the knowledge assessment scores for the traditional training program. A Wilcoxon rank sum test procedure indicated that there was no significant difference in change in the knowledge assessment test scores (for the traditional training program) based on a high or low level of education (Education), $W = 4$, $p = 0.33$.

Furthermore, a second set of correlational analyses were performed on operator performance on those questions within the final knowledge test for each of the ten sub goals with subject ratings of the frequency with which they had performed those tasks and their current level of knowledge of such skills (H4). Table 6 contains the Spearman test correlations for frequency (Frequency) and level of knowledge (Knowledge) in performing each of the ten sub-goals for programming and optimization of the HTS system and performance on the knowledge test questions for each training program.

There was significant evidence of a negative association between the frequency of the task of identifying automated devices (Goal 3) to use to perform steps of an assay and performance on those questions in the CTA-based training program, $p < .0001$. There was also significant evidence of a positive association between the level of knowledge required to develop the assay method program using SAMI® software (Goal 7) and those questions in the CTA-based training program, $p < .0001$. No other significant associations between experience and scores on the knowledge test questions were found. Correlational analyses indicated that increasing frequency of performing automation planning (Goal 3) was associated with smaller changes in knowledge assessment scores for the CTA-based training program. Furthermore, increasing knowledge of assay programming (Goal 7) was associated with larger changes in knowledge assessment scores for the CTA-based training program.

Table 6. Correlations of frequency and level of knowledge ratings versus knowledge question scores for each of the ten sub-goals.

Goal	Variable	Spearman rho	
		CTA-based Training	Traditional Training
1	Frequency	0.50	0.06
	Knowledge	-0.82	0.27
2	Frequency	-0.06	
	Knowledge	0.83	
3	Frequency	-1.00*	-0.58
	Knowledge	0.82	-0.71
4	Frequency	-0.32	-0.63
	Knowledge	0.82	0.27
5	Frequency	0.58	
	Knowledge	0.00	
6	Frequency	0.00	-0.83
	Knowledge	-0.89	-0.50
7	Frequency	0.00	0.82
	Knowledge	1.00*	0.33
8	Frequency	-0.11	0.00
	Knowledge	-0.24	0.00
9	Frequency	-0.89	
	Knowledge	-0.89	
10	Frequency	-0.83	
	Knowledge	0.00	

*$p < .0001$.

Since there was a significant linear relation between frequency of identifying automation and performance on the knowledge assessment tests for the CTA-based training program, a further analysis was performed to determine if greater experience led to greater improvements in knowledge assessment scores. A Wilcoxon Rank sum test procedure indicated that participants did not significantly improve on the knowledge test questions for the task of identifying automated devices as a result of the frequency of performing the task (median = 2.5, SD = 0.866), W = 1, p = 0.25. Furthermore, since there was a significant linear relation between knowledge required to develop the assay method program and performance on the knowledge assessment tests, a further analysis was performed to determine if greater experience led to greater improvements in the knowledge assessment scores for the traditional training program. A Wilcoxon Rank sum test procedure also indicated that participants did not significantly improve on the knowledge test questions for the task of developing the assay method program as a result of the knowledge required for performing the task (median = 2.5, *SD* = 0.866), *W* = 1, *p* = 0.25.

Furthermore, the effects of each training program on biopharmacologist knowledge structures were evaluated (H1). A Wilcoxon rank sum test procedure indicated that participants significantly improved in the knowledge assessment test as a result of the CTA-based training program (median = 0.26, *SD* = 0.10), *W* = 24.5, *p* = .03. Participants also significantly improved on the knowledge assessment test as a result of using the standard training program (median = 0.25, *SD* = 0.12), *W* = 25, *p* = .04. (It is important to note that these results also indicate no ceiling effects for performance on the initial knowledge assessment test). In comparing the degree of performance improvement on the knowledge tests (change in the scores from the initial to the final knowledge test) across the two training systems (H2), there was insufficient evidence to indicate that participants improved to a greater extent with the CTA-based training program than for the standard training program (median = 0.09, *SD* = 0.21), *W* = 19, *p* = .44.

CTA-based Training for Situation Awareness

In this study, performance on SA queries were expected to be related to initial operator experience, improve as compared to chance, and to reach an expert level of 80%.

The accuracy of biologist responses to the 72 SA questions during training trials was assessed relative to the level of performance an expert operator would be expected to demonstrate (i.e., 80%) and chance (H5). Overall SA scores and SA scores for each level were calculated for the CTA-based training program as a percentage of SA questions answered correctly (Table 7). Wilcoxon sign rank test procedures were used to assess the significance of SA performance according to chance and that expected for expert performance. Wilcoxon sign rank tests of the level of SA performance for each level of SA and overall SA scores were all significantly different from chance, $p < 0.05$, and not significantly different from the level of performance expected of an expert operator, $p > .05$.

Table 7. Proportion of SA questions answered correctly.

SA Score	Mean	SD
SA Level 1	0.84	0.07
SA Level 2	0.75	0.07
SA Level 3	0.74	0.09
Overall SA	0.80	0.07

All $p < 0.05$.

Furthermore, the amount of overall task skill, measured as number of years of experience, level of education, and initial knowledge test score for the CTA-based training program was expected to be positively correlated with SA assessment performance for each level and overall SA (H6). Table 8 contains the Spearman test correlations for level of education (Education), number of years of experience (Experience), and initial knowledge test score for the CTA-based training program (CTA-I) with the three levels of SA and overall SA. There was significant evidence of a positive association between number of years of experience (Experience) and level of education (Education) for each level of SA and overall SA, $p < .0001$. There was also evidence of a positive association between initial knowledge score and Level 3 SA scores (projection), $p = .05$.

Table 8. Correlations among years of experience, levels of education, initial knowledge test scores, and SA score for each level of SA.

		Spearman rho		
SA Level	**Variable**	Education	Experience	CTA-I
1	Education			
	Experience	1.00**		
	CTA-I	0.21	0.21	
	SA	-0.32	-0.32	0.80
2	Education			
	Experience	1.00**		
	CTA-I	0.21	0.21	
	SA	-0.83	-0.83	0.32
3	Education			
	Experience	1.00**		
	CTA-I	0.21	0.21	
	SA	0.06	0.06	0.95*
Overall	Education			
	Experience	1.00**		
	CTA-I	0.21	0.21	
	SA	-0.50	-0.50	0.74

$^*p < .10$, $^{**}p < .0001$.

A general multiple linear regression analysis indicated that Level 2 SA scores (i.e., comprehension) increased significantly with initial knowledge test scores holding level of education constant; Level 2 SA score = 1.5*initial knowledge test score + 1.5*education level – 0.5, $p = .0001$. No other relationships between SA scores and initial knowledge according to level of education or number of years of experience were significant.

Training System Usability

To ensure that the training program usability did not have a negative impact on the learning process, a heuristic evaluation was performed for the CTA-based and traditional training programs. A total of 6 usability issues were identified (M = 1.5, SD = 1) for the CTA-based training program. Two trainees indicated that there was too much textual information on the screen, resulting in 5 unique usability issues. A total of 5 usability issues were also identified (M = 1.3, SD = 1) for the traditional training program. Two trainees also indicated that there was too much textual information on the screen for this training program, resulting in 4 unique usability issues. Table 9 contains the heuristic violations identified for both the CTA-based training program (H7). Table 10 contains the heuristic violations identified for the traditional training program (H7). Since a successful design was considered one for which the training program is found to contain less than 20% of the possible unique usability problems that could be identified by expert users, and the total unique usability problems found amounted to 7% of possible problems for the CTA-based training program and 6% for the traditional training program, the training programs were considered usable.

Table 9. Heuristic-based usability evaluation for the CTA-based training program.

Heuristic	Frequency	Violations
Completeness	1	The disabled submit button functionality was not clear to learners.
Navigation	1	The media player required activation before it would start in one of the web browsers.
Organization	1	No site map or index used in training program.
Readability and quality of writing	2	There was too much textual information on a screen.
Typographic cues and structuring	1	The order of the given information did not seem to follow the order of relevance.

Table 10. Heuristic-based usability evaluation for the traditional training program.

Heuristic	Frequency	Violations
Navigation	1	Current location within training program was not clear to learners.
Organization	1	No site map or index used in training program.
Readability and quality of writing	2	There was too much textual information on a screen.
Typographic cues and structuring	1	The order of the given information did not seem to follow the order of relevance.

The overall effectiveness of the two training programs was rated by the expert users as seen in Table 11 (H8). A Wilcoxon Rank sum test procedure indicated that the subjective ratings of overall effectiveness of the CTA-based training program (M = 3.75, SD = 0.5) were comparable to (but not better than) the ratings of overall effectiveness for the standard training program (M = 2.75, SD = 0.5), W = 21.5, p = .29.

Table 11. Overall effectiveness ratings.

Strength of Opinion	**Responses**
CTA-based Training (*n* = 4)	
Positive	0
Somewhat Positive	3
Neutral	1
Somewhat Negative	0
Negative	0
Traditional Training (*n* = 4)	
Positive	0
Somewhat Positive	0
Neutral	3
Somewhat Negative	1
Negative	0

DISCUSSION

Training Improvements on Knowledge and Experience Effects on Training

The first phase of this study involved the systematic use of contemporary CTA methods such as GDTA and AH modeling, as an approach to identifying the knowledge requirements, factors underlying SA, and system components and resources required for programming and optimizing an automated assay for HTS processes. This information was used as a basis for developing training programs. This process involved the direct comparison of the GDTA results and AH models to formulate the content for different information displays within the CTA-based training program. Using the knowledge requirements identified through the GDTA, operators were instructed on how to develop key components of a mental model for HTS system operation, as it pertained to the automated subsystems, the functions of these subsystems, and the projection of future actions of the subsystems. However, since the GDTA model does not make reference to existing automated systems or software, AH models were needed to represent the purpose and function of the software and devices relevant to operator knowledge requirements.

While little current research has provided empirical evidence of the effectiveness of combined CTA methods for the development of training program design, Lintern and Naikar (1998) outlined an approach that included the use of AH models to describe a work context and to layout the constraints of the workspace that shape learning. The present study was expected to extend this work by providing preliminary validation of an integrated CTA-based training program to support biopharmacologist knowledge structures, as compared to both prior OTJ training and traditional (task-analysis based) training program design.

In the comparison of the operators' knowledge structures from OTJ training with knowledge structures based on the CTA-based training program there was significantly greater performance on the knowledge assessment test (final) after CTA-based training. While no significant difference was indicated between the CTA-based training program and the standard training program used in this study, these results can be explained by a more detailed look at how experience plays a role in training.

Based on the correlation analyses of subjects' overall prior experience with their performance on the knowledge tests for the CTA and traditional systems, the CTA-based training program appeared to be more directly related to what operators learn in actual HTS operations. The results indicated that increasing experience (number of years of experience) was associated with increasing final knowledge assessment scores for the CTA-based training program; therefore, the number of years of experience an operator had using HTS automation was particularly relevant to the CTA-based training program. Furthermore, since greater experience (level of education) was associated with greater initial knowledge assessment scores for the traditional training program, the knowledge assessment test was an accurate reflection of the role of experience in assessing knowledge.

Based on these relationships between the type of training program and the overall experience measures, a detailed comparison of the knowledge test performance for high and low education levels was conducted. The CTA-based training program knowledge test scores for "high" and "low" education operators are presented in Table 12. They reveal changes in performance indicating that the approach was more effective for less educated operators than for highly educated operators. Table 13 presents the traditional training program knowledge test scores for the same operators. Comparison of the results across tables indicates differences in performance based on the type of training program and operator education level. The operator demonstrating the least improvement in performance on CTA-based training had the greatest performance with the traditional training program. Another operator, who demonstrated the greatest improvement with the CTA-based training program, had the least improvement with the traditional training program. These differing results, according to the type of training program, suggest that there was a distinct preference in learning style or training method at play for the operators recruited in this study.

Table 12. CTA-based training program knowledge test performance based on education.

Education	CTA-I	CTA-F
High	0.68	0.82
High	0.53	0.66
Low	0.58	0.95
Low	0.47	0.79

Table 13. Traditional training program knowledge test performance based on education.

Education	TRAD-I	TRAD-F
High	0.59	0.76
High	0.29	0.65
Low	0.47	0.65
Low	0.53	0.88

Since experience in terms of the frequency of performing a task and level of knowledge an operator requires in order to perform a task can lead to differences in the operator mental models pertaining to HTS systems (Lance, Hedge, & Alley, 1989), these experience factors were considered in the evaluation of the effectiveness of the combined CTA methods. The results of the knowledge assessment tests revealed the influence of operator proficiencies reported for each programming and optimization sub-goal. A breakdown of the knowledge test results according to each of the sub-goals was evaluated to assess the relevance of CTA-based training and prior knowledge to various aspects of HTS operations.

First, a comparison of operator ratings of proficiency on each sub-goal addressed by the two training programs revealed substantial differences in background knowledge relevant to the content of the CTA-based or traditional approaches. The degree of proficiency reported by the operators was coded as zero to four: 0 – no proficiency, 1 – supporting role, 2 – OTJ supervisory role, 3 – frequently personally perform, and 4 – personally design task components of goal. These ratings indicated that half of the operators had no structured learning on at least 30% of tasks associated with CTA-based training program and one operator had structured training in 33% of tasks associated with the traditional training program (Figures 16 and 17). This suggests that with a larger sample size, operators would be expected to have greater changes in knowledge with the CTA-based training program than with the traditional training program.

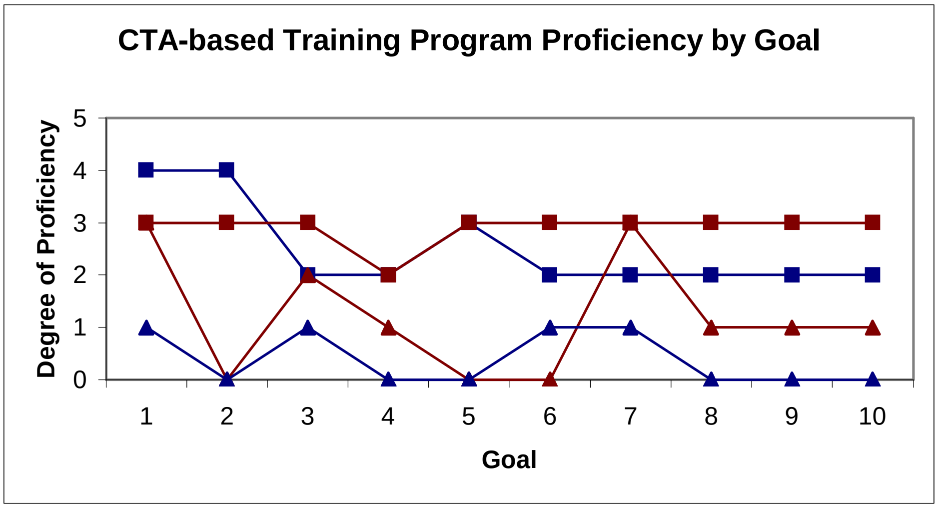

Figure 16. Degree of proficiency indicated by each operator for each goal covered by the CTA-based training program.

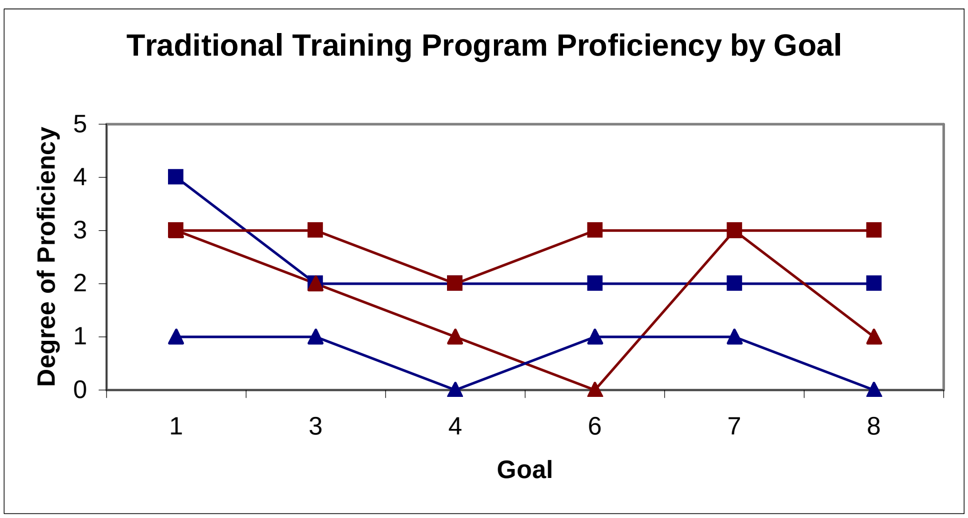

Figure 17. Degree of proficiency indicated by each operator for each goal covered by the traditional training program.

Secondly, as some of the tasks as part of assay method programming covered by the CTA-based training program are largely planning, they rely heavily on higher-level operator SA requirements (identified in the GDTA). Those that involve the use of automation for managing processes may be better supported by training based on AH model results. Those that require the integration of planning tasks and the use of automation or software, may be best supported based on the integration of both CTA methods. The results of the comparison between operator frequency and level of knowledge in performing each of the sub-goals and the performance on the knowledge tests indicated that answers to questions on two sub-goals, relying heavily on both the GDTA and AH model results, were most effected by the CTA-based training program. These two sub-goals, revealing the greatest impact in knowledge test performance from the CTA-based training, were those that required the most information from the AH models and the GDTA. These sub-goals pertained to assay planning through the identification of automated devices and assay programming using the HTS process software (i.e., SAMI®).

CTA-based Training for Situation Awareness

Due to the complexities of automation in HTS operations, one of the components of the GDTA was to provide information relating to the knowledge requirements to support SA as part of cognitive performance. Therefore, at random points within the training program, an additional interface was presented with a set of SAGAT questions targeting those subtasks recently completed. Using this technique, the accuracy of operator perceptual knowledge, comprehension of environmental states relative to the current goals and predictions of future states could be assessed and related to performance. This provided a measure of the comprehensiveness of the biopharmacologists knowledge structures following the CTA-based training program in terms the three levels of SA.

The accuracy of operator responses to the imbedded SA questions during the training trials were assessed relative to the level of performance an expert operator would be expected to demonstrate (i.e., 80%) and chance (i.e., 50%). The operators' performance on the SA questions were significantly different from chance indicating that operators were not guessing on answers to queries and achieved some improvements in knowledge based on the HTS system training program. While significant improvements were not shown for SA, according to the level that would be expected of an expert, an operator could be more knowledgeable about the critical perceptual cues that are required for comprehension and projection (Level 2 and 3 SA) following the CTA-based training.

The significant relationship of task experience with knowledge structures, as demonstrated through performance on the knowledge assessment tests, was assessed in terms of SA performance for each level and overall SA. A strong relationship between greater education and greater number of years of experience working with HTS systems was shown. Further analyses indicated that the CTA-based training program was effective in providing improved Level 2 SA (comprehension) for HTS operators (with both a higher and lower number of years of experience) beyond their initial knowledge of the system. The results also indicated that operators with more complete initial knowledge structures showed greater improvements in the knowledge structures associated with projection of future states of the HTS system (Level 3 SA). However, since the SAGAT measure did not capture knowledge structures for all three levels of SA for each of the sub-goals, a breakdown of the relationship between frequency of performing a task or level of knowledge required to perform a task and SA measures was not conducted.

Training System Usability

While few ISD models mention development of the instructional interface as a unique element (Lohr, 2000), the instructional interface should only be a means of supporting the learner in developing their mental models of the information content rather than focusing on how to access the content. Therefore, the training program procedures incorporated the three design steps of LCD (Lohr, 2000): (1) understanding the users, (2) multimedia application design, and (3) usability inspection. The training programs in this study used the GDTA and AH models to identify the knowledge required of the users, supported user motivation, encoding and retention through effective and efficient presentation of the information with multimedia features (e.g., simulations or images), and the use of a usability evaluation to address the effectiveness, efficiency and motivational aspects of the training program. Since the usability heuristics identified by Mehlenbacher (2002) take into account the conventional usability dimensions as they apply to LCD, a survey based on these 17 usability heuristics was used to evaluate both training programs.

The heuristic-based evaluation of both training programs identified few unique usability problems, suggesting the usability of the training programs did not interfere with the development of learner knowledge structures. While the traditional training program resulted in fewer total usability problems than the CTA-based training program, the differences in the total number of training program usability problems could be a result of the complexity of the training program content and design. Finally, while there was an insignificant difference in the subjective ratings for the overall effectiveness of the training programs, the operators indicated more positive ratings for the CTA-based training program than for the traditional training program. With respect to modifications to either training program based on the usability problem identification and operator recommendations, Nielsen (2006) indicated that revision should not always comply with user requests (e.g., site maps for complex training programs). He indicated that self-reported usability results may not always be reliable or reveal what the user really requires in revision. This may be due to reasons, including: the motivation of users to identify violations based on researcher expectations, limitations of retrospective memory on problems encountered, and a user's ability to rationalize their behavior to conform to the heuristics presented by the researcher. Therefore, the usability recommendations identified by this research should be carefully assessed in terms of the potential impact on training outcomes prior to implementation.

CONCLUSIONS

The purpose of the present research was to present a validated structured approach to the translation of CTA results into training program content. Furthermore, from the ISD perspective most training program development uses task analyses for evaluating tasks and not for content development, as demonstrated in this approach. Beyond this, the integration of contemporary CTA methods for training program development had not been explored. To this end, a prototype CTA-based training program was developed. The CTA-based training program design was compared with a traditional task analysis approach for HTS operations of similar complexity and with similar information requirements.

On the basis of these results, a set of general guidelines for the design of the CTA-based training programs was developed:

- Highlight information on any specific components relating to the job or environment that will be used in the performance of each task in both textual and audio presentations.
- Provide the trainees with a method for relating the current task goals to the process states at both the current sub-task and as part of the overall skill being trained.
- Provide a list of the perceptual requirements necessary to develop level 1 SA on the subtask being trained.
- Include a set of knowledge-assessment questions towards promoting operator understanding and projection of future states of the process (level 2 and level 3 SA) and provide immediate feedback.
- Use a minimum amount of textual information on each screen.
- Provide pre-training on all navigational buttons to ensure they are familiar to the learner prior to using the training program.
- Provide an overall index or site map to users of long or complex training programs.
- Provide training information in the order of relevance required by the task.

One major advantage of the CTA-based training program is the lack of the requirement for over-training that occurs with non-CTA training design methods focusing on task steps and procedures. Traditional task-analytic methods for training design require over-training on the task components that lead to comprehension of the material. With CTA-based training design this is not an issue because activities like trouble-shooting, planning, and comprehension are the primary components of these types of programs. In this study, the CTA-based training design was used to improve HTS operator knowledge structures for planning and comprehension during assay method programming and optimization by providing information requirements for each task organized according to the levels of SA (i.e. perception, comprehension, and projection). This is not possible with traditional task-analytic based training programs.

Furthermore, the combined CTA method for training program design used in this study maybe particularly important for complex tasks such as assay method programming or assay optimization, as indicated by the benefit for particular goals covered in the training program. The presentation of the SA knowledge requirements within the CTA-based training program can improve operators' knowledge structures in terms of perceptual elements in the environment, the understanding of how those elements interact, and the development of predictions of future states of the system. This is particularly important for tasks that rely on planning or programming in advance of operations. Therefore, future research that designs CTA-based training programs for the development of mental models that include the knowledge requirements as part of 'good' SA could lead to fewer operator errors in dealing with complex automation in programming tasks.

Caveats

Due to the small sample size available for this study, it is possible that the sensitivity of analyses to differences among the training conditions may have been limited. The sample size limited the number of reported measures on each training program as part of the experimental design. For this reason, distribution-free statistical procedures were used for the data sets. Since the total sample size for most of the tests performed was $n < 10$, several comparisons among the programs could not be conducted. Additionally, the small number of participants did not allow for grouping of subjects based on level of expertise, for example. However, subjects were categorized as having high or low experience and education levels and this has related to training system effectiveness. Related to this, no control group of biochemists, untrained in HTS operations was included in the study. This was due, in part, to the type HTS system analyzed. The system represents a common contemporary configuration that biochemists are knowledgeable of.

Another caveat to this research is the lack of consideration of the role of operator stress on HTS process learning. Previous research has indicated that HTS processes are more stressful in fully-automated modes than manual modes due to temporal, environmental, and job factors (Stoll, Arndt, Kreuzfeld, Weippert, & Thurow, 2008). The use of CTA-based training programs may serve to promote operator confidence and reduce stress in interacting with automation by ultimately ensuring operators have complete knowledge of SA requirements in moving from job to job and robust knowledge structures for the full range of job tasks. It would be worthwhile to assess the impact of CTA-based training for manual versus automated HTS processes and make comparisons of actual follow-on work performance and stress levels.

Future empirical research on the role of stress and workload factors in HTS operator performance should be conducted to assess the utility of CTA-based training for minimizing stress responses under fully-automated or manual modes of assay processing. Operator performance and perceived stress could be assessed both prior to and following CTA-based training for automated or manual control. Two physiological measures that may be useful for evaluating controlled effortful processing in this context include heart rate variability and neuroendocrine chemistry (Wickens & Hollands, 2000). An indicator of workload and mental effort derived from the cardiovascular system, heart rate variability (HRV), has proven to be sensitive to memory load differences in tasks with time pressure in controlled versus automatic modes of processing (Wiethoff, 1958). Additionally, cortisol has been associated with differing levels of distress during computer tasks. Therefore, both of these measures could be used to assess the physiological reactions of the operators, and stress states, under automated and manual HTS control conditions to determine the effects of improvements in operator knowledge structures associated with CTA-based training for biopharmacologists.

The results of this research included guidelines that can be used to design CTA-based training programs to promote SA and process knowledge structures in a usable format. Through the use of the structured approach to designing a CTA-based training program, instructors can provide a tool that can be used to improve the learner’s knowledge structures for complex tasks requiring comprehension, planning, and trouble-shooting. Therefore, future research might also evaluate the use of the structured approach for SA-based training program design using CTA results in the development of training programs for other domains. Another future line of research might include an evaluation of transfer of learning with CTA-based training within the HTS domain from historical to updated or similar systems for planning, controlling and analyzing HTS processes.

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APPENDICES

APPENDIX A – BACKGROUND AND EXPERIENCE QUESTIONNAIRE

Please answer the following questions, being as complete as possible.

General Information

Gender (select one): Male Female

Age: _____

Background

1. How many years have you worked as a biochemist/engineer? ______

2. How many years have you worked with life science automation? ______
   a. How many of those years have you supervised HTS processes? ______

3. Please list any degrees you have received (e.g. PhD, MA, etc.):

___

___

4. Please list any professional certifications you have received:

___

___

5. Please list any special training courses you have received in life science automation:

___

___

6. What other training or education do you have?

___

___

7. Are there skills needed to perform your job tasks that are not included in your work or educational experience (select one)? Yes No

a. If so what are they?

___

___

8. What are the duties of your position that you feel are unique to your position?

___

___

Rate your frequency of use and level of knowledge with each of the following questions. If you are unsure about an item, mark the center-point of the scale.

1. How often do you use the computer in your job?

Never		Sometimes		Frequently
1	2	3	4	5

2. What level of knowledge or skill in computer use is required to perform your job?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

3. How often do you use English language in your job?

Never		Sometimes		Frequently
1	2	3	4	5

4. What level of knowledge or skill in English language is required to perform your job?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

For each category of practice, rate the frequency and level of knowledge required to effectively perform the tasks in that category. If you are unsure about an item, mark the center-point of the scale.

1. Plan and design steps that need to be performed as part of automated version of assay:

a. Are you personally responsible for performing this task?

Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)?

____

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice, work)?

____

2. Identify and establish appropriate plate configuration and types to achieve statistically valid results:

a. Are you personally responsible for performing this task?

Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)?

____

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ________________________________

3. Identify automated devices to use to perform steps of assay:

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ________________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ________________________________

4. Adapt manual pipetting steps to automated version of assay using device software:

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ________________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ________________________________

5. Design measurement approach to facilitate analysis sample compounds using device software:

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ________________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ________________________________

6. Identify labware (deep-well plates, flat plates, tips) to be used as resource pools, transports, and sources:

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ________________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ________________________________

7. Develop program for assay method using HTS line control software (e.g., Beckman Coulter - SAMI):

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ____________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ____________________

8. Integrate pipetting device into HTS line control (SAMI) method using the methods from the device programming application (e.g., Bioworks):

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ____________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ____________________

9. Integrate incubator into HTS line control (SAMI) method:

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ______________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ______________________________

10. Integrate plate reader into HTS line control (SAMI) method using the methods from the device programming application (e.g., Fluostar):

a. Are you personally responsible for performing this task? Yes No

b. What is the nature of your involvement with this task (e.g., personally perform, supervise)? ______________________________

c. How often do you perform this task?

Never		Sometimes		Frequently
1	2	3	4	5

d. What level of knowledge or skill is required to perform this activity?

Limited, Superficial Knowledge		Some Knowledge		Extensive, In-Depth Knowledge
1	2	3	4	5

e. When or where did you learn to perform this task (e.g., school, in practice)? ______________________________

APPENDIX B – EXAMPLE TASK SCREENS IN TRAINING PROGRAMS

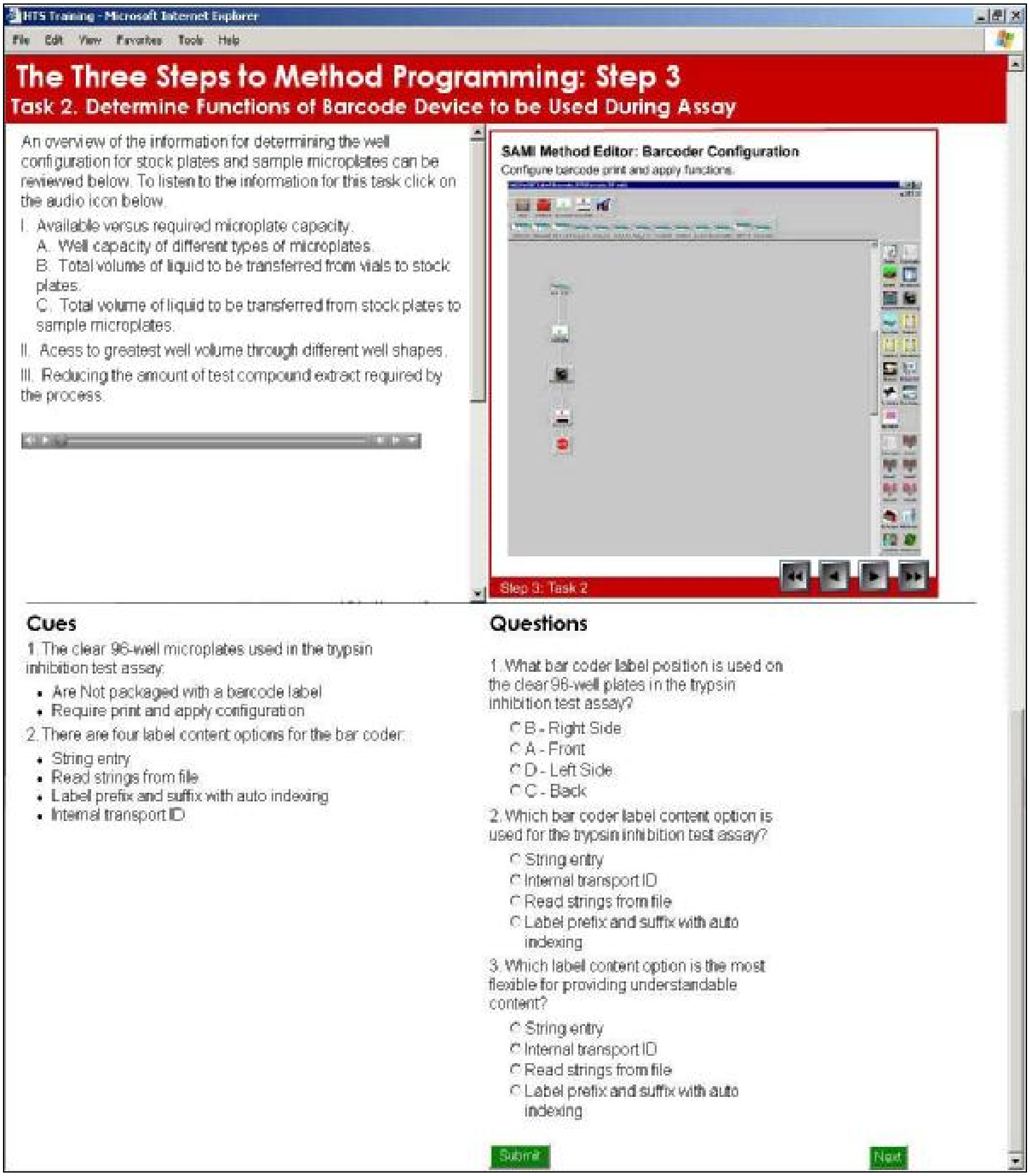
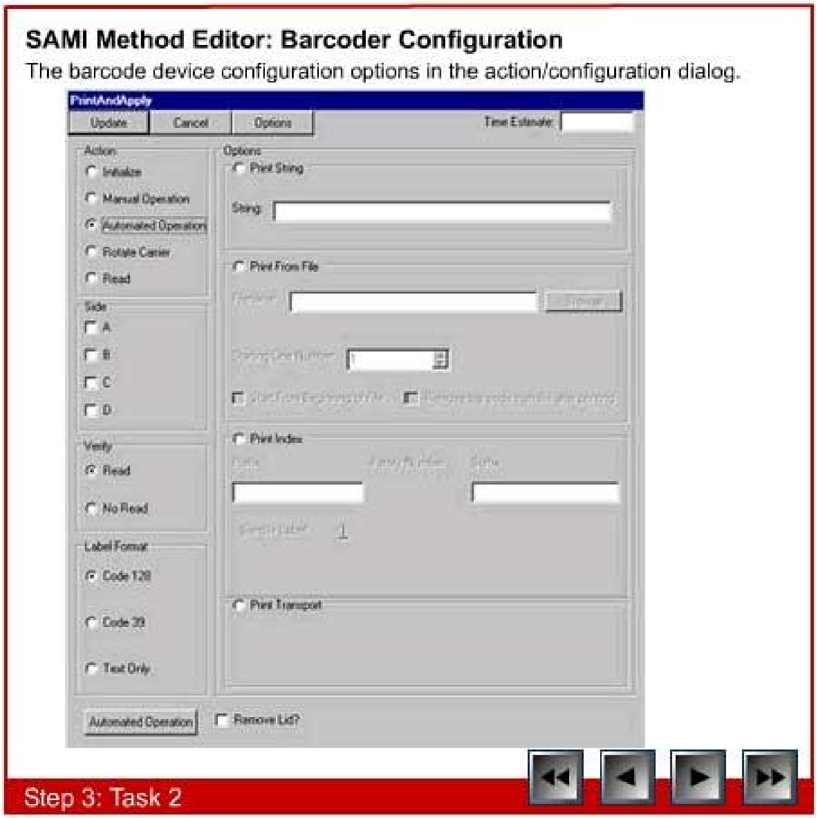


Figure 18. Task 2 of Step 3 content screen with integrated panels for CTA-based training.



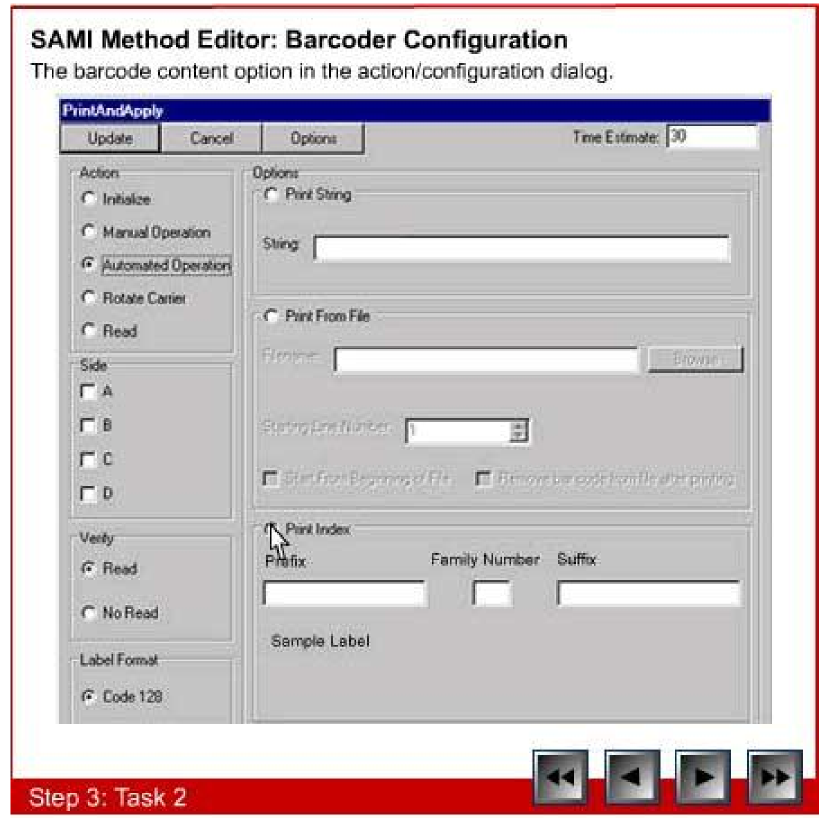
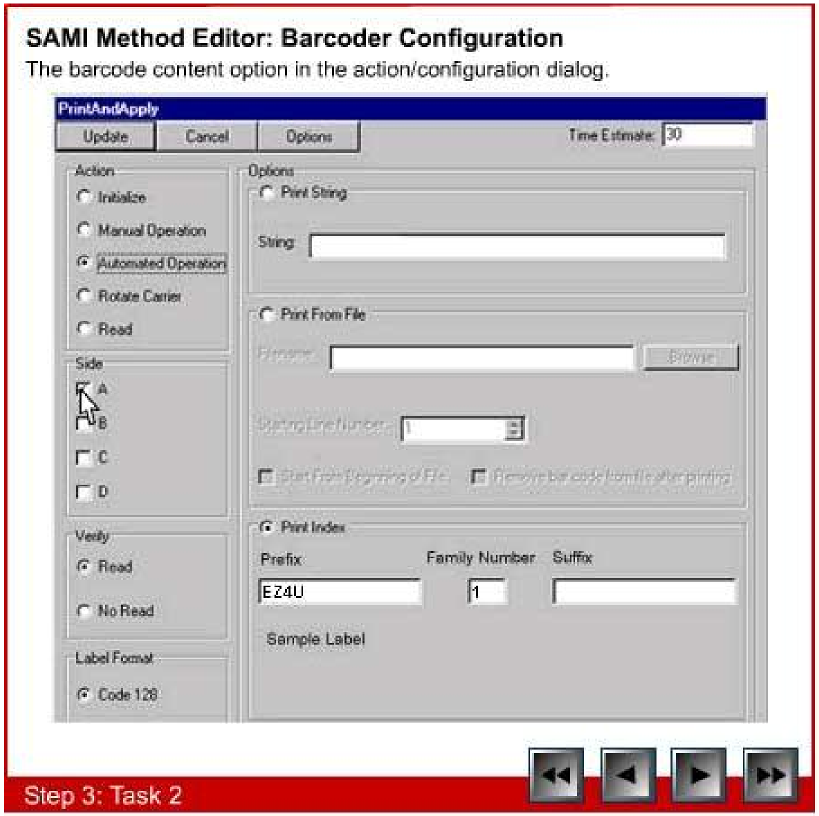


Figure 19 and 20. Screens 2 and 3 in the Simulation Panel for Task 2 of Step 3 of the CTA-based training program.



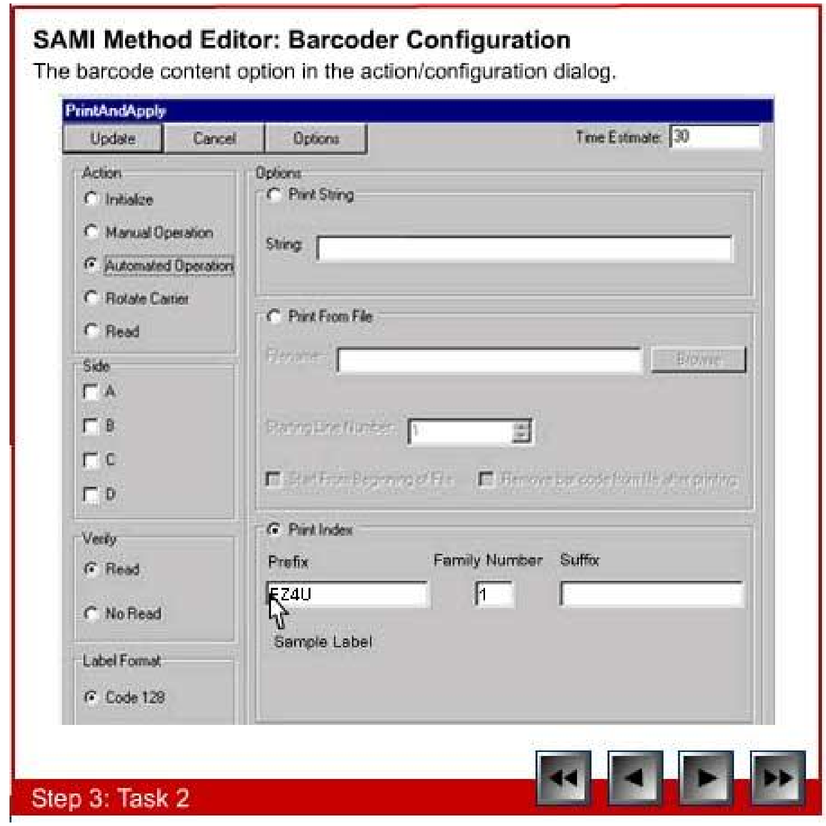


Figure 21 and 22. Screens 4 and 5 in the Simulation Panel for Task 2 of Step 3 of the CTA-based training program.

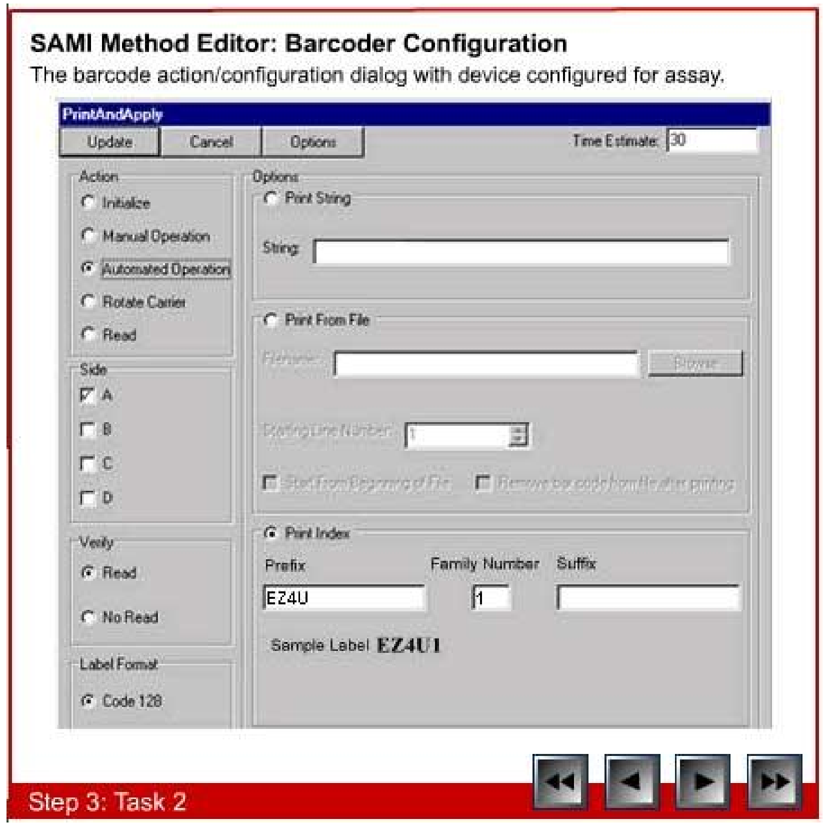


Figure 23. Screen 6 in the Simulation Panel for Task 2 of Step 3 in the CTA-based training program.

APPENDIX C – KNOWLEDGE ASSESSMENT I AND II

Please circle the correct answer for each of the following questions based on the trypsin inhibition test assay using the SAGIAN® HTS line.

1. Which of the following is an example of the general order of steps for an enzyme-linked assay?
   a. Sample preparation, addition of a reagent, and detection of the signal
   b. Sample preparation, addition of a conjugate reagent, incubation, addition of a substrate, incubation, addition of a terminal solution, and detection of the signal
   c. Sample preparation, addition of a substrate, incubation, and detection of the signal
   d. Sample preparation, addition of a conjugate reagent, incubation, addition of a substrate, addition of a terminal solution, and detection of the signal

2. Which of the following would you look for in determining if special centrifuge steps are needed in the automated assay?
   a. Pilot test data from a similar HTS assay showing need for centrifuge steps
   b. Examples in the literature using centrifuge steps
   c. Pilot test data showing the presence of liquid on the walls
   d. Review “bench-top” protocol for use of centrifuge

3. What information is necessary to determine the best well configuration for stock plates and sample microplates?
   a. Microplate well capacity, access to greatest volume is necessary, and total sample solution volume
   b. That the total liquid volume to be transferred to a sample microplate exceeds 1mL
   c. Total sample solution volume, volume of buffer, and microplate well capacity
   d. That only flat-bottom well microplates be used to permit automated microplate analysis

4. Which of the following well capacities is acceptable for the **test** microplates in the trypsin inhibition test assay?
   a. 150µL
   b. 2mL
   c. 100µL
   d. 350µL

5. How much extract is to be transferred to the wells of sample microplates from the stock plates?
   a. 5mg/mL
   b. 3mg/mL
   c. 60µL
   d. 50µL

6. Can microplates with high well-density (e.g. 384-well microplates) be used in the HTS line?
   a. Yes
   b. No

7. Which of the following types of microplates can be used in assays in which fluorescence testing is required as part of the automated assay?
   a. Clear Polystyrene
   b. Clear Polypropylene
   c. Black Polystyrene
   d. Multi-Chem™

8. Does evaporation at edge wells have a significant influence on the trypsin inhibition test assay?
   a. Yes
   b. No

9. Which microplate layout orientation provides room for a greater number of dilutions on a single microplate?
   a. Vertical orientation
   b. Row orientation
   c. Column orientation
   d. Bidirectional orientation

10. What is the order of concentrations on the test microplate in the trypsin inhibition test assay?
    a. 0.0005mg/mL, 0.001mg/mL, 0.005mg/mL, 0.01mg/mL
    b. 0.01mg/mL, 0.005mg/mL, 0.001mg/mL, 0.0005mg/mL
    c. 0.04mg/mL, 0.11mg/mL, 0.33mg/mL, 1mg/mL
    d. 1mg/mL, 0.33mg/mL, 0.11mg/mL, 0.04mg/mL

11. Can multiple compounds can be tested on a single microplate in the trypsin inhibition test assay?
    a. Yes
    b. No

12. Which type of pipetting tool can be used for transfer of samples to test microplates?
    a. MP20
    b. MP200
    c. P200L
    d. P20

13. Which type of pipetting tool can be used for transfer of stock solutions to sample microplates?
    a. MP20
    b. MP200
    c. P200L
    d. P20

14. What is the typical effective life of the Trypsin enzyme?
    a. 48 hours
    b. 13 hours
    c. 1 hour
    d. 24 hours

15. Which of the following delay times during processing would substantially reduce the activity level of the trypsin enzyme for testing?
    a. 10 hours
    b. 12 hours
    c. 1 hour
    d. 8 hours

16. Which of the following would be a maximum batch size for the trypsin inhibition test assay on the SAGIAN® HTS line?
    a. 48 families
    b. 12 families
    c. 52 test microplates
    d. 24 test microplates

17. Which **two** compounds constrain the order of pipetting steps in the trypsin inhibition test assay?
    a. Enzyme and samples
    b. Substrate and terminal solution
    c. Conjugate reagent and terminal solution
    d. Conjugate reagent and substrate

18. When should tips be changed during the enzyme addition pipetting process step in the trypsin inhibition test assay?
    a. When they will be used to measure a different reagent
    b. When throughput time will be lost
    c. When no carry over will occur in the assay
    d. When the cost of disposable tips is high

19. Tip consumption during a typical HTS run is based on which of the following sets of information?
    a. The typical consumption of the tips for one family of microplates
    b. Instances of tip reuse and the number of pipette transfer steps
    c. The reusability of the tips and the capacity of the tip boxes
    d. The number of pipetting steps in the protocol, reusability of tips within a given pipetting step, and capacity of the tip boxes

20. Which of the following is the volume capacity of the reservoirs used in the trypsin inhibition test assay on the SAGIAN® HTS line?
    a. One 37mL half-reservoir and two 18mL quarter-reservoirs
    b. Four 40mL quarter-reservoirs
    c. Two 37mL half-reservoirs
    d. One 72mL whole-reservoir

21. What order will wells be read by the FLUOstar plate reader?
    a. Replicates in columns and dilutions in row organization
    b. Row by row organization
    c. Dilutions in rows and replicates in column organization
    d. Column by column organization

22. What is the total volume of liquid to be transferred to a single well of a microplate in sample microplate preparation?
    a. 1mL
    b. 2mL
    c. 1.5mL
    d. 150μL

23. What is the ratio of dilution steps for the trypsin inhibition test assay for sample microplate preparation?
    a. 3 to 1
    b. 1 to 1
    c. 2 to 3
    d. 1 to 3

24. Which of the following controls are called for by the protocol for the trypsin inhibition test assay?
    a. Control, control blank, and sample blank
    b. Control and control blank
    c. Control blank and sample blank
    d. Sample control, control blank, and control buffer

25. Which of the following graphics show the best sample microplate layout for the trypsin inhibition test assay? (Where S_1 = Sample #1, Sb_1 = Sample blank #1, C = Control, Cb = Control blank, and X = Empty wells.)

a.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
B	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
C	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
D	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
E	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
F	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
G	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
H	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X

b.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
B	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
C	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
D	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
E	X	X	S_{10}	S_{11}	S_{12}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	X
F	X	X	S_{10}	S_{11}	S_{12}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	X
G	X	X	S_{10}	S_{11}	S_{12}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	X
H	X	X	S_{10}	S_{11}	S_{12}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	X

c.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
B	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
C	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
D	X	X	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	X
E	X	X	X	X	X	X	X	X	X	X	X	X
F	X	X	X	X	X	X	X	X	X	X	X	X
G	X	X	X	X	X	X	X	X	X	X	X	X
H	X	X	X	X	X	X	X	X	X	X	X	X

d.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
B	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
C	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
D	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
E	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
F	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
G	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X
H	X	S_1	Sb_1	S_2	Sb_2	S_3	Sb_3	S_4	Sb_4	S_5	Sb_5	X

26. Which of the following graphics show the best test microplate layout for the trypsin inhibition test assay? (Where S_{11} = Sample 1 concentration 1, Sb_{11} = Sample blank, C = Control, Cb = Control blank, and X = Empty wells.)

a.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	C	Cb	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	X
B	X	C	Cb	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	X
C	X	C	Cb	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	X
D	X	C	Cb	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	X
E	X	C	Cb	S_{21}	Sb_{21}	S_{22}	Sb_{22}	S_{23}	Sb_{23}	S_{24}	Sb_{24}	X
F	X	C	Cb	S_{21}	Sb_{21}	S_{22}	Sb_{22}	S_{23}	Sb_{23}	S_{24}	Sb_{24}	X
G	X	C	Cb	S_{21}	Sb_{21}	S_{22}	Sb_{22}	S_{23}	Sb_{23}	S_{24}	Sb_{24}	X
H	X	C	Cb	S_{21}	Sb_{21}	S_{22}	Sb_{22}	S_{23}	Sb_{23}	S_{24}	Sb_{24}	X

b.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
B	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
C	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
D	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
E	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
F	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
G	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X
H	X	S_{11}	Sb_{11}	S_{12}	Sb_{12}	S_{13}	Sb_{13}	S_{14}	Sb_{14}	S_{15}	Sb_{15}	X

c.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
A	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
B	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
C	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
D	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
E	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
F	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
G	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X
H	X	X	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	X	X

d.

	1	2	3	4	5	6	7	8	9	10	11	12
A	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
B	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
C	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
D	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
E	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
F	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
G	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3
H	C	Cb	S_1	Sb_1	C	Cb	S_2	Sb_2	C	Cb	S_3	Sb_3

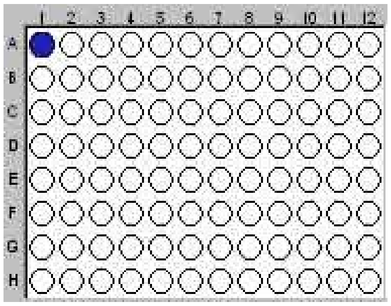
27. What is the wavelength of light identified from the “bench-top” protocol used for microplate analysis?
    a. red
    b. blue
    c. yellow
    d. green

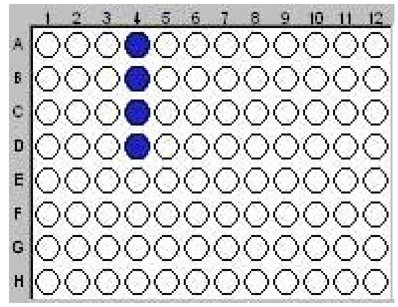
28. What two steps in the trypsin inhibition test assay can be adjusted to promote “signal” intensity?
    a. Pipetting of substrate and incubation
    b. Incubation and barcode print and apply
    c. Plate reader filter adjustment and incubation
    d. Pipetting of reagent and terminal solution

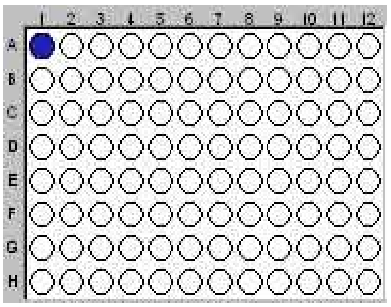
29. Which barcoder function does the trypsin inhibition test assay require?
    a. Barcode reading
    b. Automated print and apply
    c. Microplate carrier rotation
    d. Barcode alignment

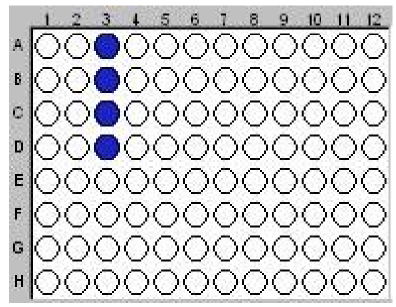
30. Which is an example of the information content that is included in the barcode label for the trypsin inhibition test assay on the SAGIAN® HTS line?
    a. String entry
    b. Read strings from file
    c. Label prefix and suffix with auto indexing
    d. Internal transport ID

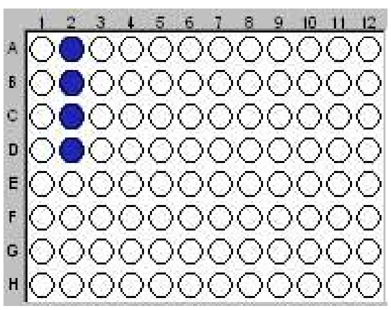
31. Which of the following graphics show source and destination wells during sample microplate preparation?

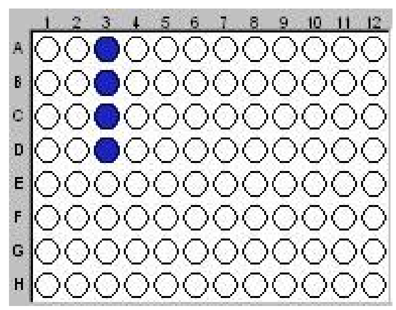
a. Source 

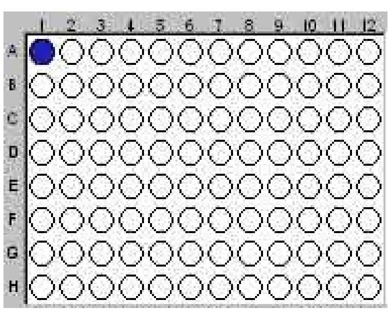
Destination 

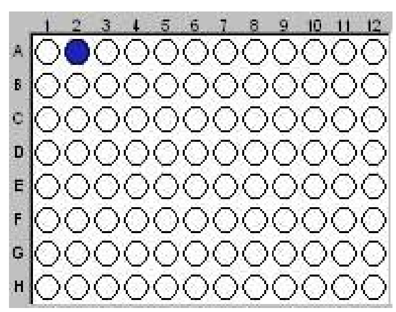
b. Source 

Destination 

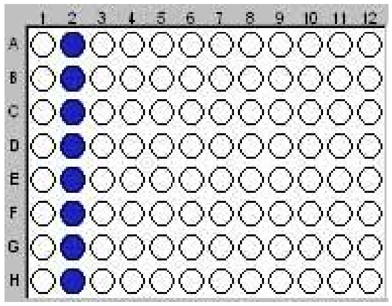
c. Source 

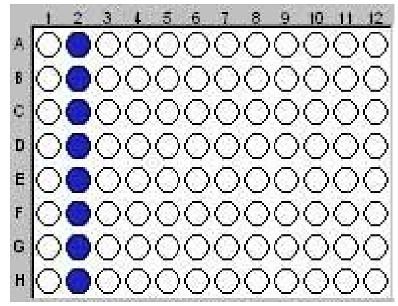
Destination 

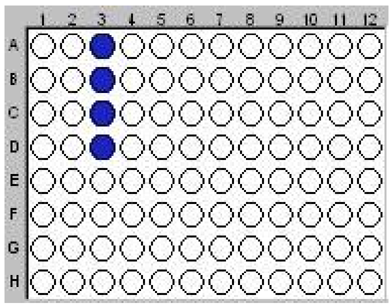
d. Source 

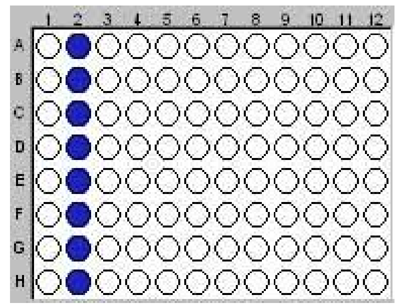
Destination 

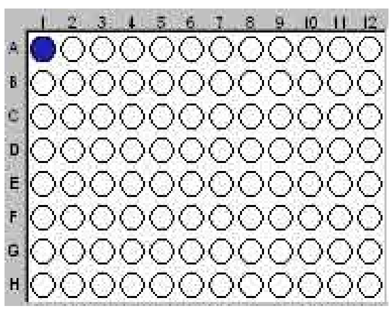
32. Which of the following graphics show source and destination wells during the first step of test microplate preparation?

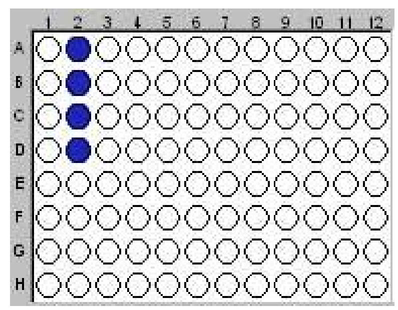
a. Source 

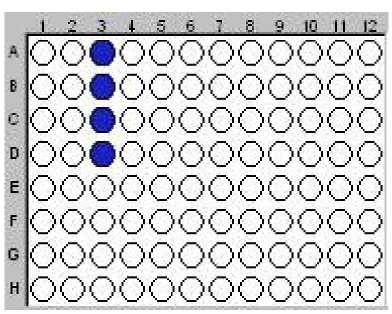
Destination 

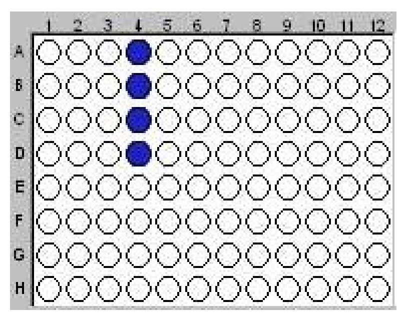
b. Source 

Destination 

c. Source 

Destination 

d. Source 

Destination 

33. Which of the following are the pieces of labware used in the trypsin inhibition test assay on the SAGIAN® HTS line?
    a. 96-well 100µL flat-bottom test microplates, 96-well 350mL flat-bottom sample microplates, and tip boxes
    b. 96-well 250µL flat-bottom test microplates, 96-well 2mL flat-bottom sample microplates, and tip boxes
    c. 96-well 250µL flat-bottom test microplates and 96 tip tip-boxes
    d. Two 96-well 2mL flat-bottom sample microplates and tip boxes

34. When is the pipetting device integrated into the automated assay method for sample microplate preparation?
    a. Before barcode reading
    b. After incubation
    c. After labware source pieces
    d. Before plate reader

35. Which of the following is a point at which the pipetting device is integrated into the automated assay method for test microplate preparation?
    a. After Barcode device and Before Incubation
    b. After Labware sources and Before Barcode device
    c. After Incubation and Before Plate Reader
    d. After Plate Reader and Before Incubation

36. What is the second incubation duration for test microplate preparation?
    a. 15 minutes
    b. 60 minutes
    c. 1 minute
    d. 5 minutes

37. What is the temperature of the incubator microenvironment required by the assay?
    a. 28ºF
    b. 27ºC
    c. 100ºF
    d. 37ºC

38. How many plate reader icons are necessary for test microplate preparation?
    a. 1
    b. 2
    c. 3
    d. 4

Please circle the correct answer for each of the following questions based on the Trypsin inhibition test assay using the SAGIAN® HTS line.

39. Can the same pipette tips be used for any solution transfers for a single plate in the Trypsin inhibition test assay on the SAGIAN® HTS line?
    a. Yes
    b. No

40. Which of the following should be identified from pilot test results for Trypsin inhibition test assay for assay optimization?
    e. Overloaded and hyper-loaded devices
    f. Device bottlenecks and optimal batch size
    g. Device re-routing and processing times for each device
    h. Optimal batch size and overloaded or hyper-loaded devices

41. What two factors determine the addition of device resources for resolving bottlenecks?
    a. Workspace available and cost of additional devices
    b. Number of devices on line and the workspace available
    c. Cost of additional devices and number of devices on line
    d. Handling capacity of each device and the cost of additional devices

42. Which of the following devices on the SAGIAN® HTS line would require a specific number of plates in a single batch for optimal results?
    a. Biomek 2000
    b. Centrifuge
    c. Incubator
    d. Shaker

43. What is an optimal batch size for minimizing the reduction of the Trypsin enzyme potency and lifetime?
    a. 26 families
    b. 52 microplates
    c. 48 microplates
    d. 23 families

44. What size of reservoir needs to be used on the SAGIAN® HTS line for a batch size of 48 microplates for the Trypsin inhibition test assay?
    a. One 37mL half-reservoir
    b. Two 40mL quarter-reservoirs and one 52mL half-reservoir
    c. One 52mL whole-reservoir
    d. Two 18mL quarter-reservoirs and one 37mL half-reservoir

45. Which of the following criteria are identified within the static scheduler as part of the process control software for assay method optimization?
    a. Number of device errors and process times
    b. Pilot testing times and scheduler results
    c. Actual process times and expected times
    d. Overloaded or hyper-loaded devices

46. What is the handling capacity (i.e. capacity for microplates) of the liquid handling device on the HTS line?
    a. One microplate
    b. Eight microplates
    c. Two microplates
    d. Five microplates

47. How many locations are there available on the SAGIAN® HTS line for 96-well flat-bottom microplates?
    a. 23
    b. 131
    c. 126
    d. 5

48. What is the lost processing time if a printer feed sensor malfunction of the barcode print and apply device occurs while processing a batch of 48 microplates on the SAGIAN® HTS line?
    a. 1 week
    b. 2 days
    c. 11 hours
    d. 30 minutes

49. Can the same pipette tips be used for multiple microplates during the reagent (i.e. Trypsin) addition step in the Trypsin inhibition test method?
    a. Yes
    b. No

50. If 493 minutes are required for the reagent addition pipetting step, would this time exceed the scheduled time for a single batch of 24 families?
    a. Yes
    b. No

51. What is the range of the total processing time for the Trypsin inhibition test assay?
    a. 8 hours to 24 hours
    b. 7 hours to 12 hours
    c. 24 hours to 48 hours
    d. 11 hours to 24 hours

How many locations are there available on the SAGIAN® HTS line for tip boxes?

a. 16
b. 8
c. 23
d. 7

52. Which of the following two components result in decisions on the optimal batch size for the Trypsin inhibition test assay process?
    a. Incubation time and reagent lifetime
    b. Incubation time and substrate addition
    c. Process duration and terminal solution addition
    d. Reagent lifetime and process duration

53. Can multiple microplates be processed in parallel on the SAGIAN® HTS line?
    a. Yes
    b. No

54. What is the maximum family size that can be processed for an optimal result of the Trypsin inhibition test assay?
    a. 1 microplate
    b. 6 microplates
    c. 4 microplates
    d. 2 microplates

APPENDIX D – EXPERT REVIEW CHECKLIST

Please evaluate each item in the knowledge assessment to ensure it successfully meets all eight of the criteria for appropriate item construction using the checklist below.

Item Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Congruent with key objective																			
Test item format is appropriate																			
Each item is on a single content category																			
Item content is independent from other items																			
Vocabulary is appropriate for learners																			
Only one response is correct																			
No clues are given on correct response																			
Test items meet all ethical and legal concerns																			

Item Criteria	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Congruent with key objective																			
Test item format is appropriate																			
Each item is on a single content category																			
Item content is independent from other items																			
Vocabulary is appropriate for learners																			
Only one response is correct																			
No clues are given on correct response																			
Test items meet all ethical and legal concerns																			

APPENDIX E – SITUATION AWARENESS GLOBAL ASSESSMENT QUESTIONS

Level 1

1. Do you need to include a centrifuge step after the pipetting process in the trypsin inhibition test assay?
2. What shape of microplate wells provides the greatest access to well "death" volume?
3. How many extracts are found on a single sample microplate?
4. What is the well capacity of the test microplates used in the trypsin inhibition test assay?
5. Are empty wells included at the perimeter of the test microplate in the trypsin inhibition test assay?
6. Which sample concentration should test microplate dilutions end with?
7. What types of pipetting tools are available with the Biomek 2000?
8. What is the typical layout configuration of a sample microplate for the trypsin inhibition test assay?
9. Where can the effective life of the enzyme be found?
10. How many total tip boxes can be contained on the SAGIAN® HTS line?
11. What is the capacity of a single tip box?
12. Which of the following is the volume capacity of the reservoirs used in the trypsin inhibition test assay?
13. How many samples are on a single test microplate?
14. What are the source and destination wells during sample microplate preparation?
15. Which of the following controls are called for by the protocol for the trypsin inhibition test assay?
16. What is the minimum “signal” intensity detectable by FLUOstar Galaxy plate reader?
17. Is an excitation or an emission filter type used in the trypsin inhibition test assay?
18. What type of test microplate is used in the trypsin inhibition test assay?
19. Is there a bar coder label on the clear 96-well flat-bottom microplates used in the trypsin inhibition test assay?
20. What starting location is used for tip boxes in the trypsin inhibition test?
21. How many depots are available within the incubator for microplates?
22. How many different solutions are used in the trypsin inhibition test assay?
23. What workbench location contains the reservoirs during the trypsin inhibition assay?
24. What other icons represent incubator locations in the SAMI method programming software?

Level 2

1. Which of the following is a typical component of a "bench-top" protocol for an enzyme-linked immunoabsorbent assay?
2. Do you need to ensure all liquid moves to the bottom of the plate wells after the pipetting process in the trypsin inhibition test assay?
3. What is the well capacity of the test microplates used in the trypsin inhibition test assay?
4. Can microplates with high well density be used on the HTS line for the trypsin inhibition test assay?

5. Does the trypsin inhibition test assay require special materials or colors for microplates?
6. What is the order of concentrations on the test microplate in the trypsin inhibition test assay?
7. How many replicates of each compound concentration provides enough room for multiple compounds to be tested?
8. Which pipetting tool is used in the trypsin inhibition test assay for transfers from the sample microplates to the test microplates?
9. What is the layout configuration of the test microplates?
10. How long does a single batch of the trypsin inhibition test assay take to complete?
11. Which two compounds limit the order of pipetting steps in the trypsin inhibition test assay?
12. What is the tip consumption for 1 family (2 microplates) in the trypsin inhibition test assay?
13. What is the ratio of dilution steps for the trypsin inhibition test assay for sample microplate preparation?
14. Which pipetting tool should be used for the pipetting steps of test microplate preparation?
15. What wavelength of light does the "bench-top" protocol for the trypsin inhibition test assay call for?
16. Does the control signal intensity of the trypsin inhibition test assay fall within the sensitivity range of the FLUOstar plate reader?
17. What is the enzyme extinction value for the control in the trypsin inhibition test assay?
18. What two steps can be modified to amplify "signal" intensity?
19. Which bar coder label content option is used for the trypsin inhibition test assay?
20. What bar coder label position is used on the clear 96-well flat bottom microplates in the trypsin inhibition test assay?
21. What are the pieces of source labware used in the trypsin inhibition test assay on the SAGIAN® HTS line?
22. What type of pipetting step will be performed for sample microplate preparation?
23. What type of pipetting step will be performed for test microplate preparation as the third pipetting step?
24. How many incubation periods are required for the test microplate preparation in the trypsin inhibition test assay?

Level 3

1. Does the total liquid volume to be transferred to a sample microplate exceed 1 mL in the trypsin inhibition test?
2. Will the sample microplate layout in the following graphic be possible given the stock solution organization for the trypsin inhibition test assay?
3. Will a well capacity of 150μL be sufficient for the test microplates in the trypsin inhibition test assay?
4. Which of the following factors would require that "clear" microplates be used in the HTS process?
5. Do reagents vary from well to well in the test microplates in the trypsin inhibition test assay?

6. Which type of microplate is used for the trypsin inhibition test assay test microplates?
7. What is the total amount of extract to be transferred to a single well of the sample microplates in the trypsin inhibition test assay?
8. Will the type of reagent to be transferred to the test microplates vary from well to well down a column?
9. If the assay run takes 26 hours to complete will the enzyme still be effective?
10. What is the maximum batch size that can be processed for the trypsin inhibition test assay?
11. Could the order of serial dilutions be altered in the trypsin inhibition test assay?
12. How many pipetting transfer steps are necessary for a single microplate in sample microplate preparation?
13. Is there enough space on the microplates for the planned number of dilutions and replications?
14. What is the layout configuration of the test microplate?
15. What is the reading that will be used in determining the color saturation for the control in test microplate analysis?
16. When should substrate concentration be increased?
17. What is the maximum signal possible for trypsin inhibition?
18. What type of microplate reading step will need to occur in the automated assay method?
19. What step comes after the bar coder in the trypsin inhibition test microplate preparation method?
20. How many instances of the barcoder device should be included in the automated assay method?
21. Will a resource pool be used in the trypsin inhibition test assay?
22. What step comes before the second pipetting step in test microplate preparation?
23. What step comes after the first incubation period?
24. What device step comes immediately before the plate reader in the trypsin inhibition test assay method for test plate analysis?

APPENDIX F – HEURISTIC-BASED USABILITY EVALUATION

Please evaluate the training interface using the following heuristics. First, indicate if a specific heuristic was violated. Then, write down the issues that constitute violations of each heuristic.

Accessibility. The electronic course interface can be viewed on different computers, with different browsers, and modem speeds.

Violated: Yes No

Violations:

Aesthetic appeal. The design should appear uncluttered, readable, and memorable. Graphics use colors appropriately and distracting graphics are minimized (e.g., movement, blinking, scrolling, and animation).

Violated: Yes No

Violations:

Authority and authenticity. The course content uses a serious tone or presence that is present, active and engaging. Humor or anthropomorphic expressions are used minimally. Direction is given for further assistance if necessary.

Violated: Yes No

Violations:

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Completeness. All levels are clear and explicit about the "end" or parameters of the course and different "levels" of use are clearly distinguishable.

Violated: Yes No

Violations:

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Consistency and layout. Every page begins with a title/subject heading that describes the contents and there is a consistent icon design and graphic display across pages or screens. The layout, font choices, terminology use, colors, and positioning of items are the same throughout the course.

Violated: Yes No

Violations:

Customizability and maintainability. Individual preferences/sections are clearly distinguishable from one another. Manipulation of the course interface is possible and easy to achieve.

Violated: Yes No

Violations:

Error support and feedback. When users scan or select something it should differentiate itself from other information chunks or unselected items. Cross-references, menu instructions, prompts, and error messages (if necessary) appear in the same place on each page or screen. Error messages should be expressed in plain language (no codes), precisely identify the problem, and suggest a constructive solution.

Violated: Yes No

Violations:

Examples and case studies. Examples, demonstrations, case studies, or problem-based situations are available to facilitate learning. Examples are divided into meaningful sections (e.g., overview, demonstration, explanation, and so on).

Violated: Yes No

Violations:

Genre representation. Task-oriented help or support materials are easy to locate and access. The “table of contents” or main menu is organized functionally, according to user tasks and not according to instructional jargon or generic “topics”.

Violated: Yes No

Violations:

Intimacy and presence. The overall tone of the course is present, active, and engaging. The course acts as a learning environment for users, and not simply as a warehouse of unrelated topics or links.

Violated: Yes No

Violations:

Metaphors and maps. The course has an easily recognizable metaphor that helps users identify additional instructional materials in relation to each other, their state in the system, and options available to them.

Violated: Yes No

Violations:

Navigability and user movement. Users can see where they are in the overall course at all times and navigation is clearly separated from content. The locations and types of navigational elements remain consistent (e.g., tabs or menus). The need to scroll or traverse multiple pages for a single topic is minimized across screens or pages. All titles, menus, icons, links, and opening windows work predictably across the course.

Violated: Yes No

Violations:

Organization and information relevance. The overall organization of the course is clear from the majority of pages or screens. Primary options are emphasized in favor of secondary and tertiary ones. A site map or comprehensive index is available.

Violated: Yes No

Violations:

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Readability and quality of writing. The text is in active voice and concisely written and terms are consistently plural, verb object or noun□verb, avoiding unnecessarily redundant words. The white space highlights a modular text design that separates information chunks from each other. Bold and color texts used sparingly to identify important text (limiting use of all capitals and italics to improve readability). Users can understand the content of the information presented easily.

Violated: Yes No

Violations:

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Relationship with real-world tasks. Terminology and labeling are meaningful, concrete, and familiar to the user. Related and interdependent course functions appear on the same screen or page. Sequencing is used naturally, if sequences of common events are expected.

Violated: Yes No

Violations:

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Reliability and functionality. All of the titles, menus, icons, links, and opening windows work predictably across the course screens.

Violated: Yes No

Violations:

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Typographic cues and structuring. The text employs meaningful discourse cues, modularization, and chunking. Information is structured by meaningful labeling, bulleted lists, or iconic markers. Legible fonts and colors employed. The principle of left-to-right placement linked to most-important to least-important information is used.

Violated: Yes No

Violations:

APPENDIX G – EFFECTIVENESS EVALUATION

1. Overall how effective do you feel the HTS Training Program was for advancing your knowledge about HTS Method Programming?

Not at all Effective		Somewhat		Very Effective
1	2	3	4	5

2. Overall how effective do you feel the Assay Optimization Training Program was for advancing your knowledge about improving the efficiency of HTS assay processes?

Not at all Effective		Somewhat		Very Effective
1	2	3	4	5