Literature review for automation skills

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I. Introduction

The purpose of this literature review is to summarize available research that is related to the concept of skill and the evaluation of skilled performance in automated environments. The review includes sections devoted to topics ranging from the broad definitions of skill to the techniques by which skills are evaluated. First, definitions and measures for various types of skill identified in the literature are presented. Skills that are specifically related to flying automated aircraft are then defined and supporting research is described. Lastly, candidate automation skills are identified and defined.

II. Definitions and Measures of Skill

In the behavioral sciences, the term "skill" refers to "a level of proficiency obtained in a specific activity" (p. 99, Baily, 1996). Skill increases as an individual develops proficiency in performing a particular activity. Regardless of the activity, skilled performances share many common elements, including goal oriented behavior, improvements in performance with practice and training, use of feedback for error correction, and conservation of cognitive resources with improved performance. In consideration of these common elements, the phrase "a skill" may then be used to describe a goal-directed activity whose performance can be improved through training or practice.

There is considerable disagreement in the literature as to the exact processing and learning mechanisms that contribute to the development of skill. However, most researchers acknowledge that three unique phases of skill development can be identified: the acquisition phase, the compilation phase, and the autonomous phase (Fitts & Posner, 1967; Sincoff & Sternberg, 1989). In the acquisition phase an individual is simply trying to understand the requirements of a new activity. An individual in the acquisition phase is still learning the task and has low levels of task-specific proficiency. Performances are slow and inaccurate. In addition, cognitive resources are limited because the individual must continuously process the activity requirements in working memory. The second phase, compilation, recognizes that the individual has a complete understanding of the task requirements and performance improves. In this phase, proficiency in the activity has increased but processing requirements still dominate working memory. During the autonomous phase, which is considered the last step in the development of skill, performance has reached a level where it appears to be effortless, where performance is almost always accurate, and where additional practice appears to make little additional improvement (Colley & Beech, 1989). In this phase, the activity seems to be performed automatically and cognitive processing requirements are low thereby freeing up cognitive resources for other activities. While performance in this final phase is typically referred to as "skilled", it is important to recognize that each phase represents a different level in the continuum of skill.

All three phases of skill development are addressed in the scientific research. Studies in this area tend to investigate the functional mechanisms involved when performing a skilled activity. These studies attempt to explain the processes involved in the development and execution of skilled performance. This is typically done using experimental designs that make comparisons between those in each phase of development, identify factors unique to each phase, and identify the limits of capacity for each phase. In this literature, "skill level" and "developmental phase" are defined by performance on the experimental task. In reality, "skill" can be considered a continuous variable that ranges from low (i.e., poor performance) to high (i.e., proficient performance). However, in an effort to establish meaningful and statistically manageable comparisons between various levels of performance, researchers often categorize “skill” into low, medium, and high levels of performance based on the learning curve of the activity.

While the aforementioned elements of skill are considered common to most activities, three general classes of “skill” have received particular attention in the scientific literature. These include *perceptual skill*, *motor skill*, and *cognitive skill*. It is important to recognize that while perceptual, motor, and cognitive components are likely to contribute to any given activity, the type of skill is inferred by the component that dominates the task. A brief description of the research performed to address each type of skill is presented below.

Perceptual skill

Perceptual skill has been defined as the proficiency level of discriminating, coding, interpreting, and classifying stimuli (Proctor & Dutta, 1995; Welford, 1976). Proctor and Dutta (1995) have identified six different perceptual skills that have been evaluated experimentally. The tasks used to study these skills are specifically designed to emphasize the contributions of perceptual skill and to limit the influences of motor and cognitive skill during performance. This is typically done by developing experimental tasks that require participants to respond as quickly as possible with a very simple and well-learned motor response (e.g, key pressing). Definitions and examples for each of these six perceptual skills have been drawn from the scientific literature and are presented below.

Detection

Activities that are used to evaluate detection typically require participants to indicate whether or not they detected a particular stimulus. For example, Bende and Nordin (1997) required participants to indicate whether they detected the presence of an odor. Ahissar, Laiwand, and Hochstein (2001) asked participants to focus on a point in the middle of a computer screen while a pattern was flashed for 250 ms. Participants were asked to respond by pressing one button if the pattern was consistent throughout the display or a different button if there was an inconsistency in the pattern. The accuracy with which participants were able to detect the type of pattern presented was indicative of detection skill. In another example, Crosby and Parkinson (1979) asked pilots flying a simulator to press a button on the yolk every time a light flashed. The accuracy with which the pilot detected the light while flying was related to the workload demands and the detection skill of the pilot.

Discrimination

Discrimination skill research typically requires participants to indicate whether or not a difference exists between a target stimulus and a secondary stimulus. For example, Cooper and Podgornoy (1976) developed a procedure that presented subjects with a target polygon followed by another polygon. The second polygon was typically presented after some defined manipulation to render it in the same shape but in a different orientation (e.g., inversion, rotation) or in a somewhat or completely different shape (e.g., mild or severe mutation). Subjects were asked to indicate if the second was the same or different than the first. The accuracy and speed with which participants were able to discriminate between the presented shapes was representative of their discrimination skill. Another activity that has been used to assess discrimination skill is the stroop test (Stroop, 1935). The stroop test presents names of colors printed in varying color ink and requires the participant to indicate if the word matches the color of the ink.

Discrimination skill is then assessed based on the accuracy of discriminating between a word of a color name and a color.

Recognition

In recognition skill activities, participants are typically asked to indicate whether a target has or has not been presented to them previously. Detweiler and Lundy (1995) presented participants with two stimuli simultaneously, a word and a pattern. After the initial stimuli, subjects were required to indicate if both the word and the shape had been shown before or if they were new. Recognition skill was evaluated by accuracy in recognizing these stimuli. Another study used a machine that converted human speech to tactile vibrations (Galvin, Blamey, Cowan, Oerlemans, & Clark, 2000). Participants were trained to recognize that specific vibration patterns represented certain words. The results demonstrated that, after training, participants were more proficient and, therefore, more highly skilled in the recognition and were able to recognize approximately 50 words.

Identification

Identification skills are usually evaluated by requiring participants to name or otherwise identify stimuli. In a study by Bende and Nordin (1997), participants were required to list different odors that were presented in various containers. Participants in this study included a group of professional wine tasters and a group of novices. It was found that the professional wine tasters were more accurate and identified more odors than the novices, indicating differing levels of identification skill. In another example, Watson, Qui, Chamberlain, and Li (1993) had participants listen through headphones to spoken words. The background noise was manipulated throughout the experiment. After hearing a spoken word, participants were asked to identify this word from a list of words that was presented before them. For example, the word 'sun' was spoken and then the words 'Fun' and 'Sun' were presented on the screen. The results indicated that the accuracy with which words could be identified increased after experience with the protocol, even when background noise was high. Other identification skill activities have used simpler protocols such as asking participants to recall lists of random alphanumeric characters (Renshaw, 1945).

Search

Search skill experiments often present participants with a target item or set of items to commit to memory. Participants are then presented with a set of items and are asked to locate the target. For example, Neisser (1963) asked participants to locate a specific string of letters from within a list of 50 strings of random letters of equal length. Pelligrino, Doane, Fischer, & Alderton (1991) asked participants to locate target polygons from lists of distracter shapes. In both experiments, the time required to find the target item(s) improved with practice but was influenced by the level of similarity of the distracters.

Memory search

Memory search skill research typically requires participants to commit a set of items to memory. Then, after a predetermined time, the target set is removed and participants are presented with stimuli and asked to indicate whether or not the stimuli were part of the original target set. Work by Fisk and Rogers (1988),Whaley and Fisk(1993), and Rogers and Fisk(1995) utilized a memory search protocol with categorical sets of words.

Motor skill

Motor skill has been defined as acquired proficiency in tasks requiring complex bodily movements or physical coordination (Mackintosh & Colman, 1995). Such proficiency requires extensive integration of sensorimotor input and output (Proctor & Dutta, 1995; Welford, 1976). This may be developed through repetition and training and by utilizing various sources of internal and external feedback.

Research in this area has sought to understand the processes involved during the acquisition and maintenance of coordinated movement (Fitts & Posner, 1967). Using simple movements in laboratory settings, researchers have tried to identify pure components of motor skill by limiting or controlling perceptual feedback cues and cognition. Activities used to study motor skill typically fall into one of two broad categories. Discrete activities are those having a recognizable beginning and end and require that a single action be performed on each trial (e.g. throwing, shifting gears in a car). Continuous activities have no recognizable beginning or end and may last for an arbitrary or a predefined period of time (e.g. swimming, flying a simulated aircraft). A third and less common category, called serial activities, has been defined by Schmidt (1988) to include those tasks that are neither continuous or discrete but seem to be made up of a series of discrete actions that are strung together and performed in succession (e.g., starting a car). Specific examples of discrete and continuous tasks that have been used to evaluate motor skill are presented below.

Discrete tasks

Simple examples of discrete tasks used in motor skill research include button pressing and typing. Each is considered a discrete task because each button or key press represents a single discrete movement. Gantner (1988) investigated movement differences between a group of expert typists (>120 words per minute), and novice typists (<60 words a minute). It was found that experts moved their fingers faster between each key press than novices. However, no differences were found between experts and novices in the distance between each key press. These results implied that the motor skill of typing involved moving the fingers faster and not using different movement strategies.

Continuous activities

A classic example of a continuous task used in motor skill research is pursuit tracking (Frolov, Sviridov, Milovanova, & Andreyev, 1991). Frolov et al. (1991) investigated the development of skill in a pursuit-tracking task. Participants were asked to manipulate an instrumented device to control the position of an image that was presented on a CRT. The objective of the task was to make the trajectory of the image they controlled match that of an image that was moving randomly (using parameters established by the experimenters). Skill was assessed by a measure of tracking error (the average difference between the position of the controlled and randomly moving images). The results demonstrated skill in the pursuit task improved (i.e., as error decreased) with practice. In addition, as skill increased, grip strength and other physiological measures of "stress" decreased.

Cognitive skill

Cognitive skill research is devoted to the investigation of human mental processing. An early definition by Welford (1976) suggests that cognitive skills link perception and action and are concerned with translating perceptual input into a skilled response by using appropriate decisions. More recently, Ericsson & Oliver (1995) stated that cognitive skill is "characterized as acquired superior performance on tasks for which perception of stimuli is easy and the required motor responses are simple and part of the subjects' repertoire of responses" (p. 38). Implicit in each definition is the interrelationship of perception, movement, and cognition. The fundamental aspect of cognitive skill research is that it aims to minimize the contributions from perceptual and motor skill and focus on the function of cognitive processes utilized during skilled behavior.

Bailey (1996) refers to cognitive skills as "intellectual skills" and states that these include both problem solving and decision making. Definitions and examples for each of these two cognitive skills have been drawn from the scientific literature and are presented below.

Problem solving

Problem solving is defined as combining existing knowledge to form new combinations of ideas in order to find a solution to a situation for which there is not a readily available response (Bailey, 1996; Davis, 1973). To investigate cognitive skill in problem solving, two predominate research paradigms have been used.

One paradigm is used to understand the development of cognitive skill. This type of research measures performance over time in an effort to track skill acquisition. This is typically done by presenting participants with a novel task and then tracking performance to observe skill development (e.g., Ericsson & Chase, 1982).

A second paradigm is used to investigate the difference in problem solving strategies between the experts and novices. For example, Chi, Glaser, and Rees (1982) investigated the strategies employed by novices and experts to solve physics problems. They found that novices relied on general problem solving methods like trial-and-error and focused on superficial aspects of the problem. Conversely, experts were found to generate mental representation of the problem that would utilize underlying physical principles (e.g., Newton's laws). They would then solve the problem using the appropriate formula based on the principle. This suggests that experts have learned to identify patterns in the problem space that serve as memory cues for previously conceived responses. Having an extensive set of cues pointing to long-term memory frees cognitive resources and serves to improve performance speed and accuracy.

Chi, et al. (1982) also indicated that experts form an immediate representation of physics problems that systematically cue their relevant knowledge. This suggests that understanding the knowledge of the expert is important in understanding the cognitive skill involved. In the case of physics, the knowledge experts have acquired is related to, but not limited to, universal laws of motion and mathematics. This means that to understand cognitive skill in a specific domain, it is necessary to identify the knowledge used by experts in that area and to evaluate quantitative and qualitative (empirical) data delineating factors unique to that environment.

Decision Making

The difference between problem solving and decision making is not always an easy distinction to make. The distinction, however, is useful to highlight different types of cognitive skill. While problem solving generally involves creating the correct solution, decision making generally involves choosing the most desirable option among a number of alternatives.

The research provides further insight into decision making, in general. This is useful in understanding the elements of decision making related to the use of automation and automation modes. Specifically, Orasanu (1993) and colleagues have investigated the role of decision making in the flight environment (Orasanu, Dismukes, & Fischer, 1993;

Orasanu & Fischer, 1995; Orasanu & Strauch, 1994). These authors have delineated different types of decisions and have identified factors that contribute to decision-making skills. They recognize that decision tasks require pilots to differentiate between relevant and non-relevant information, integrate information to produce a correct interpretation of the situation, generate possible options, assess options, determine risk, set priorities, execute the most viable option, and evaluate outcome feedback. This indicates that decision making is a complex process that requires perceptual and cognitive skills.

In the flight deck environment, multiple decision processes may be required simultaneously. Typically, the decisions that receive the most attention are those that lead to errors, but decision making is used in all aspects of flight. Decisions related to automation use include choosing to use the automation instead of hand flying, choosing the appropriate level of automation, and choosing the correct mode for each phase of flight (Orasanu & Fisher, 1995). Variables affecting automation skill decision making performance are inadequate evaluation of the situation, a lack of situation awareness, mistaken mental model of the automation, being out of the loop of the current situation, getting behind the plane, and being unaware of previous mode transitions executed by the automation.

Automation mode selection is an important aspect of flying an automated aircraft. Different phases of flight and operational situations require different modes to be used. The Flight Deck Automation Issues web site (Funk, Lyall, Wilson, Niemczyk, & Vint, 1999) indicates that moving among levels and modes of automation during routine flight is crucial to safety. The majority of reasons indicated as relevant to efficient mode changes were factors within the pilot's control. Effective decisions to use varying modes of automation are affected by accurate situation awareness, an accurate mental model, understanding of the automation, and knowledge of the requirements of different phases of flight and operational situations.

Orasanu (1993) has pointed out that all decisions made in the flight deck are made by the crew, not just by one pilot. The flight crew could be considered the decision-making team as defined by Orasanu and Salas (1991) in their work on team decision making. They contend that team dynamics impact how decisions are made and define variables that contribute to effective team decision making. Specifically, four variables have been identified as relevant to crew decision making. These are situation awareness, metacognition, shared mental models based on explicit communication, and efficient resource management. These authors found that crews with excellent performance records had high levels of these factors, while crews with lower performance had varying levels of each.

Measures of cognitive skill

Cognitive skills are generally measured through accuracy of performance and a measure along the dimension of time. The measurement of accuracy is used for evaluating both types of cognitive skills: decision making and problem solving. Accuracy determines what the level of freedom from mistakes the performance was.

Along the time dimension, the measurement used differs depending on the type of cognitive skill that is being measured. For problem solving, speed of performance is the measurement generally used(e.g., How much time is required for the user to solve the problem presented?). For decision making, pattern of timing is used as the measurement along the time dimension. Pattern of timing evaluates when various elements of the performance occur. For example, an expert may spend additional time at the beginning of the performance evaluating the situation than a novice does employing a trial-and-error strategy (e.g., see Chi, Glaser, & Rees, 1982).

Skills Related to Flying Automated Aircraft

Defining automation skills

Only a limited number of studies have investigated the components of skill used in the automated environment (i.e.., Degani, Heymann, Meyer & Shafto, 2000; Harris, Goernert, Hancock, & Arthur, 1994; Hilburn, Mouloua, & Parasuraman, 1994; Mosier, Heers, Skitka, & Burdick, 1997; Orasanu & Fischer, 1995; Riley, Lyall, & Wiener, 1993; Sarter & Woods, 1992, 1994). These studies have identified a number of variables that are relevant to flying automated aircraft. Some of these include decision making, teamwork, experience with automation, training, flying experience, mental models, situation awareness, mode awareness, choice of mode, human-machine interaction (HMI), and reliance on automation. Empirical research in this area has been approached from a number of avenues including laboratory tasks, questionnaires, incident analyses, and flight simulators. Although the research has not directly assessed the definition or assessment of automation skills, the results and variables used provide insight into these questions.

Our research project is focusing on the skills related to the use of flight deck automation. It is useful to consider types of flight deck automation rather than addressing automation as a broad concept. Three types of automation have been defined: control automation, information automation, and management automation (Fadden, 1990; Billings, 1997). The functions of control automation are to control and direct the airplane. The functions of information automation are related to the management and presentation of flight-relevant information. And the functions of management automation are to permit strategic planning and control of the aircraft operation.

As previously stated, a description of a skill is a statement about the level of proficiency demonstrated on a specific activity. The group of skills of specific interest in our research includes those related to activities for which their proficiency makes up the more general proficiency of flying an automated aircraft. In other words, these are the skills associated with operating an automated aircraft that are not required for flying a non-automated aircraft. We will refer to this group of skills as automation skills.

Automation skills are associated with the proficiency of new activities or tasks required for pilots to operate an automated aircraft. Research has shown that flying the automated aircraft requires a change to the role of the flight crew, including requirements for some new tasks to be performed and for changes to the performance of other tasks (Sarter & Woods, 1992, 1994; Billings, 1997).

The activities or tasks associated with using each of the three types of flight deck automation are different. Therefore, it seems that the skills associated with them will also be different for the three types. The use of control automation requires the engagement of the automated systems (i.e., autopilot or autothrottle) and then the monitoring of the aircraft and its systems to ensure proper control. The skills associated with accomplishing these activities are likely to be dominantly perceptual and cognitive skills as described in previous sections.

The use of information automation requires the requesting and receiving of relevant information and the format for presentation of that information (i.e., map display or traditional navigation display format). The motor skills required to request the information are minimal compared with the requirements for choosing and understanding the information. Therefore, for these skills we expect cognitive skill components to be dominant with contributions from perceptual and motor skills.

The use of management automation is similar to the use of information automation except that the motor skill component is expected to be increased because of the need to enter data about navigation plans and other strategies into the flight management computer. The skills required in the use of management automation are expected to have significant contribution from all three categories of skill.

Candidate automation skills

As an initial set of candidate automation skills for our research, we have drawn from those that have been treated in the literature as skills related to the use of flight deck automation.

In the literature, most skills that have been associated with the use of flight deck automation are dominantly cognitive skills. Following is a list of each of those cognitive skills grouped by the type of automation to which it is related:

Control automation

- Monitoring of automation (Sarter & Woods, 1994)
- Anticipation of automation behavior (Sarter & Woods, 1994)
- Decision to use control automation (Riley, Lyall, & Wiener (1993)
- Mode management or decision making related to use of modes of control automation (Sarter & Woods, 1992, 1994)
- Automation management to control aircraft (Sarter & Woods, 1992, 1994)
- Control aircraft using automation
- Navigate aircraft from one place to another using automation (Sarter & Woods, 1994)
- Management of automation failures (Sarter & Woods, 1994)

Information automation

- Gather appropriate information using automation (Sarter & Woods, 1994)
- Decision to use information automation
- Mode management or decision making related to use of modes of information automation (Sarter & Woods, 1992, 1994)

Management automation

- Decision to use management automation
- Management of flight using automation [referred to as human-machine cooperation by Hoc (2000)]

Even though the majority of skills in this group are cognitive skills, perceptual and motor skills also contribute to the use of automation. One such perceptual skill is that of maintaining awareness of status of systems and other flight parameters (i.e. situation awareness). Data entry to the flight management computer is a related motor skill.

As can be seen by the listing above, Sarter and Woods (1992, 1994) have investigated a number of different components of automation skills. Sarter and Woods (1992) surveyed 135 B-737-300 pilots having more than one-year experience. The survey asked pilots to provide detailed descriptions of instances when automation did not do what they expected (termed “automation surprise”). It was found that over 50% of the pilots had experienced automation surprise. The cause of this was due primarily to the pilots’ inexperience with specific FMS modes and transitions between them. Pilots reported that they had only moderate confidence in their ability to utilize all modes and that certain modes and mode transitions were more problematic than others. Also, when certain modes were engaged, situation awareness decreased or was lost. A second aspect of this study observed pilots who were not experienced with automation as they transitioned into an automated aircraft. Initially, inexperienced pilots would use a prescribed flight plan and trial and error to operate the FMS. This suggested that their mental model of the FMS was incomplete because they did not use the optimum modes. Inexperienced pilots used the modes they were familiar with and tried to tailor the flight plans to maximize use of those modes. In addition, they were more likely to make mistakes transitioning between modes, indicating that they did not fully understand the function of each. As understanding of the system developed, pilots’ errors and questions shifted toward gaps in their understanding of the underlying functional structure of the system. This helped to complete their mental model of the automation. These findings demonstrate the acquisition of skill in using the FMS.

Sarter and Woods (1994) then developed a simulator protocol to investigate the limitations of pilots’ mental models of the FMS. The protocol design was based on the automation surprise reports of the experienced pilots and the observations made of the training pilots. A 60-minute scenario was designed to make pilots utilize FMS modes that were identified previously as being problematic. Twenty pilots, 14 with considerable line experience and 6 about to finish training, completed the experimental flight condition. It was found that only 5 pilots (20%) had trouble with routine tasks, while 14 pilots (70%) had difficulties with non-normal conditions. Automation-related errors were higher for the trainees than for the line pilots. This indicates that regular interaction with the FMS improved pilots’ skill in using the system. In addition, line pilots and trainees were found to use different strategies to execute various tasks in the scenario. Line pilots appeared to use strategies that reflected a deeper understanding of the functions of the FMS modes indicating they had a more detailed mental model of the system. This study indicated that experience with automation impacts pilots’ mental model of the automation and both experience and mental modelare important elements to understanding pilots’ ability to use automation correctly.

Riley, Lyall, and Wiener (1993) have investigated the cognitive skill involved in making the decision to use control automation. In their study, they investigated the pilot’s decision to use flight deck automation in two ways. A simulator study was conducted to observe pilots making decisions about when to use automation given seven different situations, and a questionnaire was administered following the simulator session requesting the pilots to describe the factors that influenced their decisions to use (or not use) the automation. The study was conducted with 40 A320 pilots; 20 captains; and 20 first officers, who averaged over 1,500 hours flying the A320. During the simulator sessions, pilots were presented with seven ambiguous situations aimed at investigating variables that may affect automation use decisions. Following the simulator portion of the study, pilots completed the automation use questionnaire. The simulator results supported the idea that urgency, risk, uncertainty, and workload influenced the pilots’ decisions to use automation. The questionnaire further revealed that the majority of pilots reported that risk, urgency, confidence in manual control, confidence in automation, trust, workload, and reliability were all factors that regularly influenced their decision to use automation. They also indicated that other factors, including distractions, weather, traffic, system malfunctions, time to input information, need to keep up hand-flying skills, fatigue, cockpit observers, desires of the captain, and quality of training had an impact on their use of automation.

III. Conclusion

The fundamental purpose of this literature review was to summarize the available research related to the definition, identification, and assessment of skill, particularly as it pertains to the automated flight deck environment. We have described three major veins of behavioral skill research and have provided examples from each. The measures used to quantify perceptual, motor, and cognitive skills have then been synthesized in an effort to define automation skills and describe the skills required to fly automated aircraft. These candidate skills have been organized by the type of automation used and should provide a well-grounded foundation for identifying and assessing automation skills from simulator data.

IV. Bibliography for the automation skills literature review

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