

Evaluation of complex and dynamic safety tasks in human learning using the ACT-R and SOAR skill acquisition theories

Samuel A. Oyewole^{a,*}, Amey M. Farde^b, Joel M. Haight^c, Oladapo T. Okareh^d

^a John and Willie Leone Family Department of Energy and Mineral Engineering, The Pennsylvania State University, University Park, PA 16802, USA

^b Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, University Park, PA 16802, USA

^c Human Factors Branch, CDC-NIOSH Pittsburgh Research Laboratory, Pittsburgh, PA 15236, USA

^d Department of Epidemiology, Medical Statistics and Environmental Health, Faculty of Public Health, College of Medicine, University of Ibadan, Ibadan, Nigeria

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ABSTRACT

This paper provides a human-centered analytical approach to learning dynamic and complex tasks using the Adaptive Control of Thought-Rational (ACT-R) and the State, Operator And Result (SOAR) models by comparing the task times of the model and the subjects. Twenty-one full time assembly line workers at a local computer company (14 men and 7 women) from ages 18–32 (Mean = 19.86 years, SD = 0.96 years) were randomly selected for this analysis. The task involved the placement of printed circuit board (PCB) components on the flow line of the desktop computer mother board manufacturing process. The overall timed performance of the subjects indicated that the match between the model and the subjects was good, resulting in an R^2 – value of 0.94. At the unit task level performance, and R^2 – value of 0.96 for placing the PCBs on the flow line. For tasks involving picking and searching of PCBs, the obtained R^2 – value was 0.76 and R^2 of 0.68 at the keystroke level. Findings revealed that the model already started out with a complete strategy of performing the task, whereas the human participants had to acquire additional learning information during the trials. Efforts will be made in the future to determine how the performance of the human subjects could be enhanced to meet or the same level as the model performance.

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1. Introduction

Skills are acquired and used in almost all aspects of the human life. In the academic field, skill acquisition is needed in every area of learning such as sociology, economics, linguistics, psychology, artificial intelligence, and most importantly in the area of human factors and ergonomics. Several definitions have been provided to describe skill such as expertness, and practiced ability or knowledge (Attewell, 1990). In simple terms, skill could be described as the ability to do something well, in a competent and proficient manner. Skills are usually learned or acquired. Examples of skills include driving a car, swimming, communicating effectively, and management or decision making skills. Several types of skills have been identified, but the common skill types include perceptual, cognitive, communicative, and motor skills (Newell, Rosenbloom, Laird, & McCarl, 1991). Skills are acquired through learning and performance can be improved through practice. Skill acquisition is often measured in terms of improvement in the speed of performance.

According to VanLehn (1996), the most extensively studied skill in the field of cognitive science is the cognitive skill acquisition.

Cognitive skill acquisition can be defined as the attainment of the ability to solve simple or complex problems involving mental or intellectual tasks. In cognitive skill acquisition, success is based on the level of knowledge or prior information that the subject has been able to acquire within the practice time frame. Common cognitive skill acquisition activities usually involves learning to solve intellectual tasks problems such as puzzle solving, arithmetic, and elementary geometry (Anderson, 1982; Rosenbloom, Laird, & Newell, 1993).

Until the late 1950s, several research studies have investigated skill acquisition and performance on the determination of the best methods for training motor skills with emphasis on those methods that allowed for faster learning and a greater transfer of motor skills and muscular performances to different situations and tasks (Pear, 1948). Theoretical analysis of skill acquisition involving quantitative research studies began with the study of what causes the factors which makes problems difficult to be solved (Duncan, 1959). Before then, several research works have been done to examine complex skills and skill acquisition. Early studies of complex skills began with the study performed by Bryan and Harter (1899). Their investigation was based on the examination of the learning curves obtained when subjects were trained to send and receive Morse code signals. In their study, they observed the plateaus in the learning curves of the receiving task. The plateaus

* Corresponding author. Tel.: +1 814 863 4491; fax: +1 814 865 3248.

E-mail address: sao152@psu.edu (S.A. Oyewole).

are the periods of non-improvement in the performances of the subjects during the training session. Their findings indicate that further training of the subjects resulted in improved performance.

As a result of this, Bryan and Harter proposed that skill learning involve the acquisition of a hierarchy of habits. Interestingly, some modern theories of skill acquisition have been influenced by this proposition. Book (1925) performed a similar test by training subject on how to type. The typewriting experiment showed the same results with that of Bryan and Harter (1899). In 1836, Samuel Morse and Alfred Vail developed the electric telegraph which sent signals or pulses of electrical current to control an electromagnet which was located at the other end of the telegraph wire. The Morse code was developed for the electric telegraph for easy communication between the sending and receiving ends. The Morse code could be described as a type of character encoding method which transmits telegraphic information using a set of rhythm. The Morse code uses a standardized sequence of short and long elements to depict letters, numerals, punctuation as well as any special character of a message.

This paper considers more recent cognitive skill acquisition models such as the Adaptive Control of Thought-Rational (ACT-R) and the State, Operator And Result (SOAR) to determine whether the human subjects acquire learning skills more effectively (when compared to the model performance) during dynamic and complex tasks in a computer manufacturing assembly line production or not. The ACT-R and the SOAR models were combined and compared to the task times of the human subjects. Section 2 provides a detailed literature review on the previous and recent research efforts in the field of cognitive skills acquisition. In this section, contemporary skill acquisition theories (MacKay, Crossman, Logan, SOAR and ACT-R) were highlighted, including their respective applications and limitations have been provided. Section 3 provides a justification for the combination of two or more of these theories. The ACT-R and SOAR theories were combined and a model was developed to determine the effectiveness of the combined model. The experimental methodology and research procedures are highlighted in Section 4, while Section 5 enumerates the results and discussion of the task analysis. This work is concluded in Section 6.

2. Literature review

Early researches in skill acquisition were aimed at the determination of whether part training on a task could be more effective than whole training. For example, training of air pilots could be done in phases on the ground and in the air. In this example, it may be difficult to combine land and air training in a single phase (McGeoch & Irion, 1952). In reality, the decision of adopting part or whole training is often dependent on the task. Contrary to training pilots in phases, Welford (1968) argued that whole training is a more efficient learning means than part training, especially in tasks which highly involve interrelated activities. The issue of task practicing was another area of research interest in early studies of skill acquisition. This involves the determination of the best method of practicing a task in one long session (massed) or spaced (distributed).

In determining the best practice, researchers faced the problem of defining the training efficiency in situations, where the training cost is dependent on the training time and the length of time of the testing. Even with this particular constraint, several studies have proposed distributed training methods as the most efficient (McGeoch, 1931; Welford, 1968). This proposal has been criticized by Adams (1987) based on the notion that distributed practice only improves the momentary level of performance and does not

necessarily improve learning. Other early areas of research interest in skill acquisition studies include the determination of whether improved performance could be achieved without the knowledge of results. Barlett (1948) claimed that practice performance is not improved without the knowledge of results. In order to observe skill acquisition improvement, the learning curves have been used to plot the relationship between performance and practice. In most cases, the learning curves show increasing performance based on improved practice (Ferster & Skinner, 1957). Snoddy (1926) noted that when the logarithm of performance is plotted against the logarithm of the amount of practice, a linear relationship (straight line) is obtained. This linearity in relationship indicates that performance time could be described as a power function of practice (power law of learning).

The process of problem solving in skill acquisition began in the 1960s with the research work conducted by Fitts in 1964. Fitts (1964) suggested that motor skill acquisition occurs in three phases (early, intermediate, and late). In the early phase (termed as the cognitive stage) the subject tries to understand the knowledge domain without trying to apply it yet. This stage often lasts only a few trials since the subject is still trying to understand the instructions and develop the performance strategies. This phase is dominated by activities such as reading, discussion, and gathering of other general information. It should be noted that observations are not always collected by most investigators during the early phase. In the intermediate phase (associative stage), the performance strategy is refined. In problem solving, prior examples are often studied to correct any initially acquired flaws in the domain knowledge and to strengthen the relevant previously learned strategies that are needed for the new situation. This process leads to new associations between relevant stimulus clues and responses. It should be noted that unintended errors or slips could still be made at this stage (Norman, 1981).

In the late phase (autonomous stage), subjects are less guided by cognitive control or external interference and more autonomy is achieved. This makes it possible for lesser processing of the skilled performance of the task thereby providing more processing resources for other activities. In this stage, the speed and accuracy is improved with practice without changing the basic approach and understanding of the domain. It should be noted that as skills continue to be faster and more efficient, the rate of improvement begins to reduce with practice. Although Fitts did not propose any theory of skill acquisition, the description of the sequence of events proposed for the development of a skill could be identified as the foundation towards the establishment of the major contemporary theories in skill acquisition.

The major contemporary theories of skill acquisition could be divided into two broad categories. The first category includes theories that suggest the importance of practice as a mechanism of performance improvement. This is based on the assumption that practice provides an effect for refined procedures needed for improving tasks. Examples of such theories include the Adaptive Control of Thought-Rational (ACT-R), Newel and the State, Operator And Result (SOAR). The other category includes theories that assume that performance improvement is a by-product of some of the consequences of practice. In this category, some theories are based on the assumption that practice leads to increased knowledge which then leads to improved performance. An example of this category of theories of skill acquisition is the instance theory. Other contemporary theories of skill acquisition include the connectionist model, the exemplar-based random walk theory, Crossman's theory, and MacKay's theory (Speelman & Kirsner, 2005). Other contemporary theories include the Logan's Instance theory and the Connectionist models (Rumelhart, McClelland, & The PDP Research Group, 1986).

2.1. MacKay's theory

This was originally developed by MacKay in 1982 to examine how a cognitive event could be translated into muscular response. MacKay's theory is applicable to several types of skilled human behaviors, especially complex skills and speech production. MacKay's approach is based on the development of a hierarchical network of interconnected nodes which represent skilled behavior (MacKay, 1982). The network is developed in such a way that if an idea is needed to be expressed as a speech, it would have been originally envisaged in a conceptual system as a series of propositions which are then linked to a phonological system. The linked propositions and phonological systems are then converted into phonological information. During the translation process of the phonological information, the decision of which muscle to move is made. This is necessary in order to make the required sounds in a muscle movement system (MacKay, 1982). The strengthening of the connections between the nodes increases the level of fluency in behavior which is due to practice. For example, stronger connections are established between the propositional nodes, the phonological nodes, and the relevant muscular nodes when a sentence is repeated multiple times. Stronger node connections indicate that activated nodes are able to prime the other connecting nodes which are lower to them in hierarchy. This leads to greater fluency due to the faster rate of activation of the lower nodes.

MacKay's theory is noted to account for the power law of learning based on the proportional relationship between the rate at which a node is activated and the priming rate. The priming rate can be described as the function of the historical frequency at which the node is activated by a connected node in the past. This implies that an unpracticed node will show speedy improvement with practice, while nodes with intermediate practice will show moderate improvement with increasing practice. Nodes with high frequencies of past priming history may not have enough room for improvement. The performance speed of a task is based on the overall performance of all the nodes involved in the task. It should be noted that performance is dominated by the nodes with little prior practice early in the practice of a task, thereby making the performance improvement to be large. One of the major limitations of MacKay's theory is that with an increasing rate of practice, the learning rate is reduced since all nodes are now further along their learning curves and are slowly improving.

MacKay's theory accounts for the transfer of training to some degree. The identical element view is described by MacKay's theory in terms of the hierarchical nodes. The elements are represented by nodes which indicate specific aspects of the skill. The rate at which a practice of a task is transferred to the performance of a second task is determined by the rate at which both tasks engage the same nodes. In order to determine this relationship, MacKay (1982) reported that bilingual subjects were considered and were made to repeat a sentence several times in one of their fluent languages and then were made to repeat the sentence aloud in the other language. The findings show that substantial transfer occurred since the sentence was read faster in the second language than the first. This high rate of transfer is due to the sentences expressing the same idea and sharing the same node at the conceptual level, even though they may not necessarily share several nodes at the phonological and muscular level. Additionally, using MacKay's theory, nodes at the phonological and muscular levels are known to be over practiced; therefore they may not lead to improvements in performance necessary for transfer.

2.2. SOAR theory

The SOAR theory (also known as the Newell and Rosenbloom's theory) is used to provide accounts of numerous cognitive

situations and has been widely used in several domains such as the performance of simple tasks, the Sternberg item recognition paradigm, typing, verbal learning, crypt-arithmetic, syllogisms, and sentence verification (Newell, 1992). The SOAR theory has been shown to be similar to the Adaptive Control of Thought (ACT) theory in several aspects (Laird, Newell, & Rosenbloom, 1987; Newell, 1990; Rosenbloom, Laird, Newell, & McCarl, 1991). Newell (1990) proposed SOAR as a possible candidate for the unified theory of cognition. Newell (1990) claimed SOAR can be used in several ways. For example, qualitative predictions could be made from SOAR as a verbal theory, without even performing actual computer simulations. The obtained qualitative predictions could cut across all varieties of cognitive behavior (domain-general) or could be specific to a particular behavior (domain-specific).

This theory has also been developed as computer software which provides the opportunity for phenomenal simulation and the comparison of observed and predicted data. This has been applied to specific domains by developing comprehensive computational models of a task which involves the addition of domain production rules to its long term memory, and generating behavioral traces. SOAR is considered a production system since it assumes that behavior occurs as a result of the execution of several production rules. All tasks and activities are considered as problems in SOAR. These problems are solved by the execution of productions, and productions can be executed only if the task and production conditions match. A pseudo-conflict resolution technique which occurs as a part of the decision cycle is used to resolve conflict situations (Newell & Rosenbloom, 1981).

All productions could be executed to resolve conflicts in the decision cycle; however, the behavior is not controlled by all conflict resolving productions in situations, where multiple productions respond to the same situations. Production execution involves the addition of new knowledge to the long term memory. The incoming knowledge could include preferences concerning which decisions or behaviors are better than the other. At the end of each decision cycle, sorting of preferences are performed in order to determine which behavior could be considered as the most appropriate. The performance of the selected most appropriate behavior is then used in commencing the next decision cycle. Impasses often occur in situations, where the productions in the long term memory are not sufficient enough to determine which next step is to be taken. When impasse occurs during the processing of a sub-goal, SOAR develops a technique for performing tasks by creating a hierarchy of the goals and sub-goals. In this case, the impasse is treated as a problem and sub-goals are set to resolve them. Using several strategies for dealing with conflict, the SOAR uses its impasse resolving methodology to make the necessary knowledge concerning the right next step to take again.

The ability of the SOAR to encounter conflicts and resolve impasses provides learning opportunity. A new production is created when impasses are resolved; also a new condition is created. The condition created for the new production represents the elements of the working memory at the time of the impasse, while action represents the solution taken. The benefit of this is that it is not necessary to go through the same process again in situations, where similar impasses occur. In this case, SOAR recommends the retrieval and execution of the previous successful solution. The ability of SOAR to remember and retrieve past solutions to problems is known as chunking. This is an enormous advantage when compared to having to solve the same problem again each time it occurs. Chunking is used in complex tasks to combine the behavior of several chunks into new ones. Therefore, whenever the same task is to be performed again, less problem solving and easy retrieval of solutions is achieved. This enables SOAR to provide an account for the power law of learning. Since there are numerous opportunities for chunking to occur due to the initial

stages of practice, the negatively accelerated aspect of the power law of learning is increased, thereby leading to large gains in speed performance. This negatively accelerated aspect in the learning curve is taken into consideration by SOAR using chunking while ACT-R theory accounts for the negatively accelerated feature of the learning curve by invoking a strengthening mechanism.

An increasing rate of practice reduces the opportunity for chunking to occur, thereby leading to a lesser rate of performance improvement. Some of the limitations in SOAR are that the productions that occur due to chunking are virtual entities of the problem solving process and could extend beyond the conditions which they were initially acquired. It should be noted also that productions are executed only when their conditions have been met. This could make it difficult in situations, where production conditions cannot be met. Another limitation of the Newell and Rosenbloom's theory (SOAR) is that it assumes no strengthening of the response to an individual chunk once it is learned. Thereby making this theory highly applicable to situations in which the stimuli are highly patterned, which allows for the formation of chunks at several levels (Logan, 1988).

In terms of transfer, SOAR uses a similar technique to ACT-R, however, the occurrence of transfer between two tasks are limited by the extent at which the developed productions could be used for one task, then the other. In comparison to his own (Instance) Theory, Logan (1988) argued that the SOAR theory may not be very applicable to lexical decision making and alphabet arithmetic experiments since it may be impossible to perform some tasks. Some of the shortfalls of Logan's Instance theory do not provide adequate flexibility in the prescription transfer process. This has led to a wide spread suggestions for the modification of Logan's theory (Logan, Taylor, & Etherton, 1999; Logan & Zbrodoff, 1999).

A major limitation of the SOAR is that it uses its chunking mechanism to breakdown the stimuli into chunks, then the chunks are responded to at different levels. Also, the SOAR model has been criticized for failure to live up the expectation of addressing very complex systems based in its uniformity assumptions that all tasks are problems or problem spaces, all long-term memory are productions, and all learnings are chunking. This assumption has been criticized to have been developed against the predominant mode of theorizing in both cognitive psychology and cognitive neuroscience. The leading theoretical method emphasizes functional specialization and distinctions over computational generality (Cooper & Shallice, 1995).

2.3. Crossman's theory

Crossman's theory is considered as one of the early contemporary theories of skill acquisition. It is based on the assumption that practice leads to performance improvement. Crossman (1959) suggests that more efficient strategies are adopted with increasing practice when performing new tasks. With practice, the outcomes produced are monitored with the types of strategies used until the fastest one is discovered. Crossman investigated this theory by allowing the subjects to sample different methods for performing a task until the fastest strategy is found. The research was based on the assumption that there was a pool of possible strategies which could be selected by subjects at random for each performance task to be evaluated.

Crossman's theory does not imply that the strategies are modified by practice, but practice allows the opportunity to select the most efficient strategy. The speed of the selected method was then compared to their average speed over several trials. If the selected method was faster than the average speed, the probability of selecting it for the next trial is increased. If this is continued, in the long run, the fastest method would have the highest probability of being selected. This theory predicts a power-function

speed-up because a faster method could be easily found early in practice than later on. It should be noted that more efficient methods become very difficult to find with increasing practice, thereby reducing performance time.

Crossman's theory accounts for the power law of learning by claiming it is easier to find faster and more efficient methods early in practice, thereby improving the performance within a reasonable time. Crossman's theory is applicable to situations with different methods of performing a task and when the subjects have a prior knowledge of all the different methods that are available at the beginning of the task. A major limitation of this theory is that there is no provision for learning newer methods or improving on the old ones as practice progresses. One of the notable pitfalls of the Crossman's theory is that it does not provide comprehensive information on skill transfer and the origin of the strategies. Crossman's theory may be very effective for the acquisition of motor skills such as typing, but it would not be appropriate for tasks such as lexical decision and alphabet arithmetic which involve developing newer methods and strengthening the older ones.

2.4. ACT-R theory

The Adaptive Control of Thought-Rational (ACT-R), also known as the Anderson's theory is one of the most important and comprehensive theories of skill acquisition. The earlier versions of the ACT-R theory include (ACT-Electronic) – ACTE (Anderson, 1976), ACT for factory production systems – ACTF (Anderson, Kline, & Beasley, 1979) and (ACT star) – ACT* (Anderson, 1982). ACT-R (Anderson, 1993; Anderson & Lebiere, 1998) is the current version of the theory. The ACT-R is an improvement of the earlier versions. ACT-R is considered as a general theory of cognition that describes an architecture which incorporates all the cognitive processes thereby qualifying it as a possible candidate for a unified theory of cognition (Newell & Yost, 1989). The ACT-R is incorporated with several learning mechanisms such as translating verbal instructions into procedures for performing a task, generalizing and differentiating existing procedures, composition and strengthening. A flow chart to depict the cognitive architecture proposed by ACT-R is shown in Fig. 1.

Although it is widely used in other cognitive processes, the ACT-R uses production rules which are activated by the working memory (Anderson, 1983). The use of production systems in ACT-R is not limited to the description of behavior, but is also sensitive to psychological and empirical constraints. Based on this, verifiable predictions could be made. ACT-R is capable of distinguishing between declarative and procedural knowledge. Declarative knowledge could be described as the representation of facts. For example, a green traffic light is a signal to go. Procedural knowledge could be described as the representation of what to do in a particular situation. In this case, actions are based on the presence of some conditions. Procedural knowledge is incorporated with production rules–condition–action pairs associated with the presence of a particular data pattern in working memory with the performance of a particular action. When a condition of a production rule is satisfied, the production can then apply and the action will proceed. For example, **IF** a traffic light is green, **THEN** go. The ACT-R production system provides some constraints for the activation of productions which include:

1. Productions can only be activated by the knowledge that is currently active in the working memory.
2. The speed at which the condition is matched to the data in the working memory is a function of the production strength.

In terms of conflict resolution, ACT-R uses the original three rules utilized by ACT* which determines the production that will

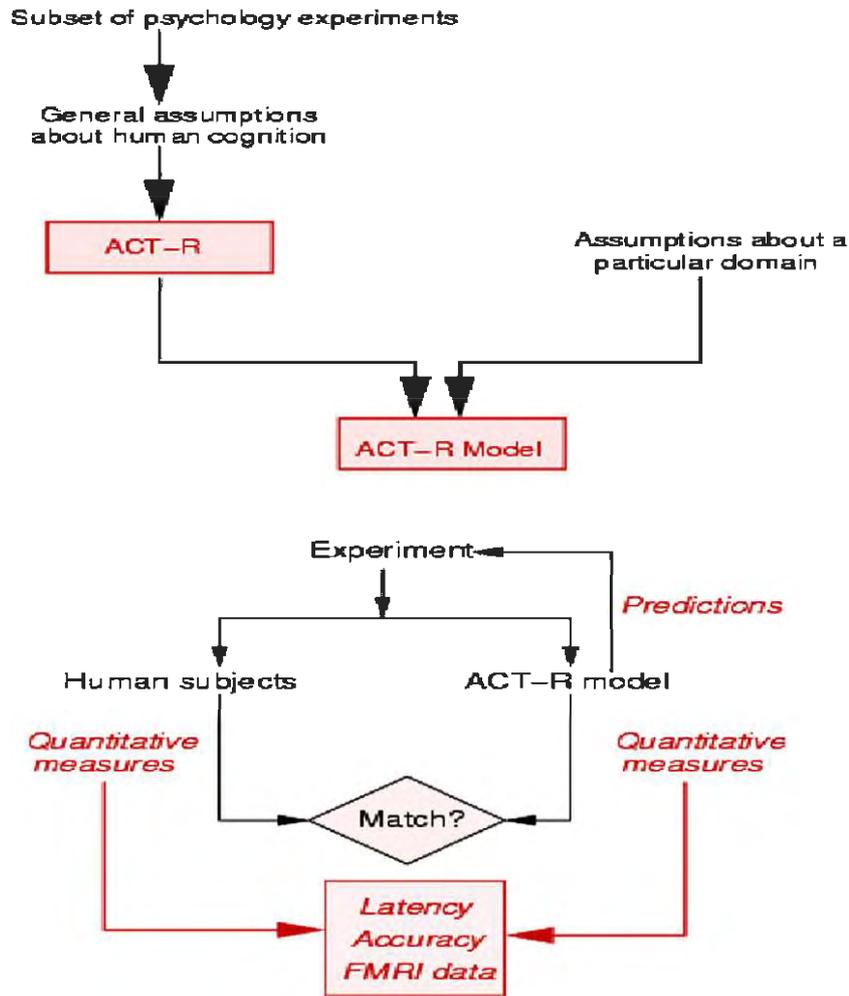


Fig. 1. Flow chart depicting the cognitive architecture of the ACT-R.

apply when the conditions of more than one production is matched by the working memory data. In the ACT-R, the general sequence of activities in skill acquisition includes:

1. Knowledge relevant to the performance of a skill begins in a declarative form. This knowledge is interpreted by weak problem solving methods which are domain-general (not specific to any to any particular task).
2. Domain-specific productions are created by the process known as compilation. Compilation involves proceduralization and composition. Proceduralization involves using weak problem-solving methods to create domain-specific productions as a by-product of the interpretation of declarative knowledge. Composition could be described as the breaking down of numerous steps into one by combining adjacent procedures. The level of practice necessary to reduce a complex procedure to a single step is dependent on the number of steps as well as the probability of combining adjacent steps.

More steps reduces the probability of combining the adjacent steps, the number of steps are reduced by a constant proportion on each iteration of the procedure, thereby producing increased learning in the early stage of practice. Learning becomes slower with increased practice. Strengthening could be described as the process of increasing the speed of executing productions. Strengthening operates mainly on composed productions, by increasing the exposure strength by a constant proportion on each of the

iterations of the procedure. Strengthening and composition collaborate together in order to produce the power-function speed-up. Although, the learning mechanisms may contribute to the speed-up in one form or the other, composition and strengthening are the known major contributors. Anderson (1982) showed the impact of compilation and strengthening on the power law of learning. This is based on the assumption that productions increase in strength with practice, thereby resulting in faster utilization of the productions which eventually becomes smaller with increased practice.

ACT-R describes how transfer occurs between tasks by identifying production rules as the components of the knowledge involved in the transfer. This means transfer between tasks is based on the extent to which productions involved in the performance of the first task is useful in the second task. The three forms of transfer considered are the positive, negative and zero transfer. Positive transfer occurs when knowledge developed in one situation is transferred to the other (Kieras & Bovair, 1984). Negative transfer occurs in a situation, where the performance of a task is worse than if a preceding task had never been performed (Anderson, 1987). Zero transfer occurs when training in one task will not provide any performance benefit for another task if the two tasks do not share the same productions (Singley & Anderson, 1989).

The ACT-R is considered as being more detailed with cognitive learning mechanisms which are stimulus-specific or could be generalized to provide process-based learning. This theory could be applicable to situations, where people learn general procedures

rather than specific responses to specific stimuli. One important attribute of ACT-R is that it distinguishes itself from other theories by providing the opportunity for researchers to collect quantitative data which can be compared directly with the quantitative measures obtained from human subjects. ACT-R successfully created models in numerous cognitive domains such as learning and memory, problem solving and decision making, language and communication, perception and attention, cognitive development, or individual differences.

Apart from its applications in cognitive psychology, ACT-R has been used in other fields such as human–computer interaction to produce user models for evaluating different computer interfaces, education (cognitive tutoring systems) for predicting and providing help on student difficulties, computer-generated forces, and in neuropsychology, to interpret functional magnetic resonance imaging (fMRI) data. Although the composition process may be effective in situations, where the task structure work allows the collapse of adjacent steps, the ACT-R may, however, not be applicable to tasks involving lexical decision or alphabet arithmetic involving one single-step process. This provides the justification of the combination of the ACT-R with one or more notable theories to compliment this limitation.

3. Model development

Several researchers have focused their attention on the development of numerous computational models for learning simple tasks, while skill development of complex and dynamic tasks is often neglected. It is therefore important to use the skill acquisition theories to develop an empirical model for studying simple and complex tasks. A combination of the ACT-R and SOAR theories would provide the opportunity for evaluating complex and dynamic tasks that are more specific to human learning. This combination is necessary to account for the limitations of both theories since each theory could compliment the other. In a similar study which also investigated the combination of ACT-R and SOAR, Lee and Taatgen (2002) proposed production composition for multi-tasking activities. Production composition is a theory of skill acquisition which combines aspects of the theories proposed by Anderson (1982) and Newell and Rosenbloom (1981).

The ACT-R/SOAR model is therefore, proposed for a computer simulated task involving the placement of printed circuit boards (PCB) components on the flow line (assembly line) of the desktop computer mother board manufacturing process. In a typical motherboard assembly line, several tasks are involved. The stages involved in the assembly of the computer motherboard include the application of solder paste to the bare PCB and the PCBs are then sent to the next employee (assembler) for the next stage. The next stage of the assembly process is to pick and place the tiny resistors, solid-state capacitors and other integrated circuit (IC) chips onto the PCB with great precision (some components are as small as 1 mm²). Each board is then sent to the next assembler to ‘**small pick and place**’ and ‘**large pick and place**’ devices. At this stage, additional components are placed on the motherboard. When all components are added, the final product is sent to the next section for quality control and inspection.

Using the three stages of skill acquisition: the cognitive stage, the associative stage, and the autonomous stage proposed by (Fitts, 1964), the incorporation of these stages into the proposed model has been found very useful. The three stages could be described as moving from conscious processing, slow and error-prone to unconscious processing, fast and error-free. Anderson (1982) described these stages as a transition from declarative knowledge to procedural knowledge. In the cognitive stage, knowledge is assumed to be declarative which needs to be interpreted. Knowledge

interpretation in this stage is slow and may lead to errors if the appropriate knowledge cannot be retrieved at the right time. Procedural knowledge is considered as compliable thereby making it fast and free of errors. The procedural knowledge is associated with the autonomous level (stage 3). The second stage, known as the associative stage, could be described as a transitional stage during which knowledge could be partly declarative and partly compiled.

Newell and Rosenbloom (1981) proposed the use of chunking in the SOAR theory. Chunking is considered an important component of the SOAR cognitive architecture (Newell, 1990) due to the numerous benefits described in the earlier review of SOAR theory. In SOAR, skill acquisition is achieved by combining production rules and by converting the current goal context into new and more specialized ones which are summarized in all the processing required to achieve a specific sub-goal. This is necessary so that the recurring of a particular problem is processed based on the initially learned rule for solving the same problem (Taatgen & Lee, 2003). The ACT-R/SOAR model incorporated the characteristics of both Anderson’s and Newell and Rosenbloom’s theories of skill acquisition. The proposed model involves both the compilation of declarative knowledge into procedural knowledge as well as the combination of several production rules into new single rules. The ACT-R/SOAR model is used for the development of a detailed computation technique of learning the tasks involving the placement of PCB components. The placement of PCB on flow line tasks is chosen since it is a considerably complex task which simulates the dynamic aspects in real life product development.

3.1. The task

In the computer manufacturing assembly line production system, the PCBs are often upgraded with newer versions and models. There is therefore, a huge need for the human picker to select the right PCB component in order to prevent manufacturing defects or the production of sub-standard computers. It will be important for the subjects to be able to acquire the skills necessary to effectively pick and place the PCB components onto the motherboards efficiently. The activity selected for this research involved the picking up and placing of the PCB components on the flow line within a time frame. For the first time, the picking up and placement of small motherboard (PCB) components is as study tasks in the study of cognitive skill acquisition. This is a task which is composed of the following elements displayed on the screen using the combination of the ACT-R/SOAR (a) eight PCB component placement positions, (b) four flow lines, (c) information on the current number of PCB components, penalty points, (d) conditions for the flow lines, and bottleneck, (e) delaying of the placement of PCB, (f) three message windows, one for notifying the need of PCB, one for providing feedback on errors, and the last one for displaying of the rules of the task in response to information requests by the participants. The eight placement positions are divided into two levels corresponding to two placements on each flow line, one placement for large components and one placement for small components. Six rules govern participant’s actions in this task: (1) PCB must be properly placed on the flow line, (2) PCB placement could only be delayed if all flow lines are busy, (3) PCB can only be placed on one flow line at a time in that level, (4) PCB components could only be placed on the available flow lines, (5) PCB components cannot be intentionally delayed (delay can only be activated due to bottlenecks), and (6) Only one PCB can be picked for placement at a time.

Participants can execute three actions in this task: (a) They can **SEARCH** for PCB components from the inventory, (b) Can **SELECT** or **PICK** PCB components from the inventory, and (c) Can **PLACE** the PCB components on a flow line. This can be accomplished by using four keys: the Up-arrow and the Down-arrow keys, (↑) and (↓); the

F4 function key, F4; and the Enter key (↵). They can move the cursor up and down the placement positions on the flow line using the up arrow key (↑) and the down arrow key (↓). They can **ACTIVATE** the delay of the PCB placement due to bottleneck by using the F1 key. And, they can **SELECT** a PCB component from the inventory, **PLACE** the selected component in the delay position, or **PLACE** the component directly on the flow line using the (←) key. In addition, participants can press the number keys 1–6 to examine the rules 1–6 any time during the task. They are given 25 points for placing the PCB component on the flow line, penalized 50 points for causing bottleneck, and penalized five points for holding too much inventory. A bottleneck occurs when there are too many components on the flow line and piling up occurs. PCB components are added to the inventory every 5 s and once a component is placed in the inventory, it cannot be removed.

For this task, it is anticipated that the model will outpace the human subjects in the overall performance. A similar methodology has been used in the development of complex tasks, especially in the case of the air traffic control systems. Lee and Anderson (2000) developed a model of expert performance in the air controller task using the Adaptive Control of Thought–Rational/Perceptual-Motor – ACT-R/PM (Byrne & Anderson, 1998) cognitive architecture. They observed that expertise in the Kanfer–Ackerman Air Traffic Controller (KA-ATC) task requires a substantial degree parallelism between cognition, perception, and action. When the subjects become skilled in the air controller task, their performance was largely limited by the constraints on the motor system (Ackerman, 1988; Ackerman & Kanfer, 1993; Kanfer, Ackerman, Murtha, Dugdale, & Nelson, 1994). Also, Taatgen (2001) developed an alternative to the ACT-R model to examine individual differences on practice performance and learning speed.

This was achieved by the manipulation of ACT-R parameters corresponding to working memory capacity, speed of production composition and psychomotor speed. Findings of the research reveal similar patterns in the relationship between individual differences and performance. The proposed ACT-R/SOAR model accounts for perceptual and motor interaction with the interface. This model could be used for controlling the placement of various manufactur-

ing components, can be useful in queuing theory, nuclear plants, and air traffic control (Taatgen & Lee, 2003). The ACT-R/SOAR model also accounts for the changes in the needs of the user by allowing the participant to switch from small components to large components and vice versa. There is no penalty to changes? in the user requirements.

3.2. Task analysis

Fig. 2 shows the decomposition task-analysis for the picking and placing of PCB components. The task analysis is based on the method of unit task analysis suggested by Card, Moran, and Newell (1983) for the decomposition of task into increasing specific goals, down to the keystroke level of basic cognitive goals.

As shown in Fig. 2, the picking and placing task is decomposed into three unit-tasks which are: (a) **PICKING** and **PLACING** the PCB on the flow line, (b) **PICKING** and **DELAYING** the placement of the PCB, and (c) **SEARCHING** the inventory to **INSPECT** PCB components for quality. Each unit-task is then decomposed into different functional-level goals. For example, the unit-task of picking and placing PCB directly on the flow line involves: (1) the determination of which PCB component (large/small) is needed, (2) searching of the inventory for the availability of the component and for quality, (3) selection of the desired component, (4) finding a flow line to place the PCB, (5) moving the PCB component to the desired flow line and, and (6) placing the component on the flow line. These functional-level goals require a number of keystroke-level goals which include a sequence of attention shifts across the screen. The information in the screen is encoded in order to allow the keystroke to carry out the designed action. A computer mouse could also be used for the operations performed by the keystroke.

3.3. Model description

The basis for the ACT-R/SOAR model is that instructions are represented in declarative memory which needs to be retrieved and interpreted. The production rules which interpret the declarative instructions are not task-specific and can be used for multiple

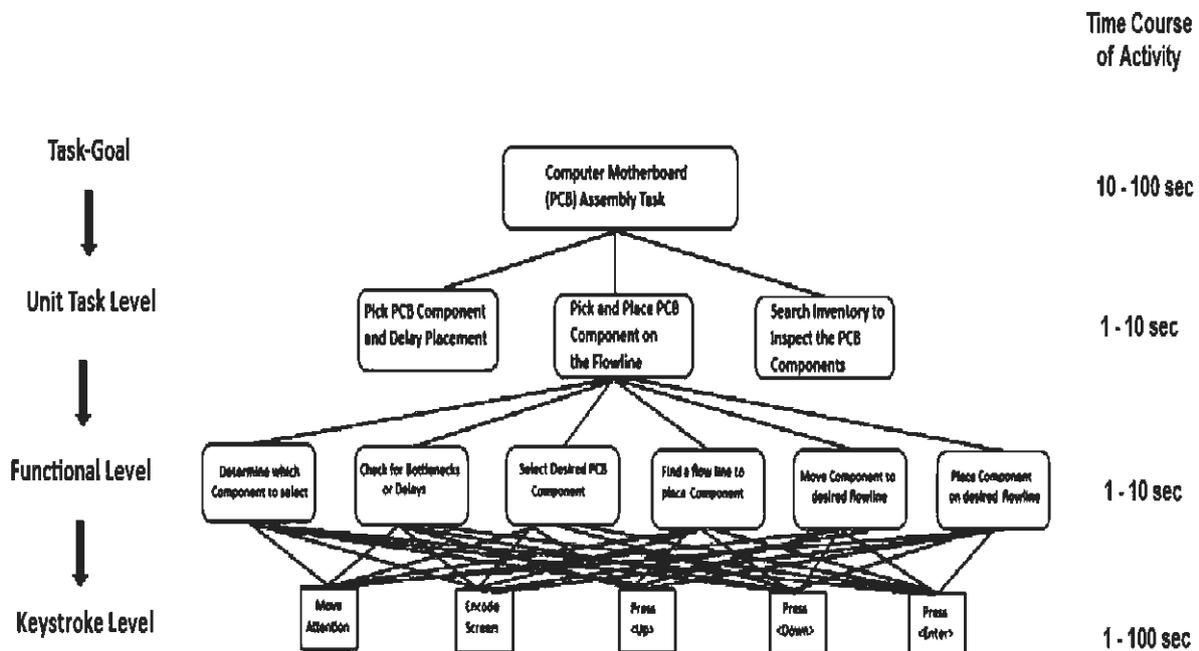


Fig. 2. Hierarchical task decomposition of the task (Adapted from Lee & Anderson, 2001).

tasks. The declarative representation is categorized into the goal level and the level of sequential individual steps which must be taken within a goal. For example, to place a PCB component on the flow line, the instruction is to first search to see whether there are any available flow lines, and to search the inventory to find the appropriate component for the PCB on the flow line. Based on this goal, another goal is selected such that if all flow lines are full, then delay placement will switch to another component size. In order to achieve the goal of picking and placing the PCB component on the flow line, the production rules could be as follows:

1. A request is made to the declarative memory so as to retrieve the next level of instruction.
2. As soon as the declarative memory produces the required instruction, it is stored in the goal.
3. A request is then made to the declarative memory for the retrieval of the component which must be perceived.
4. As soon as the declarative memory produces the location of the component, a command is then issued to the visual system to move the eyes to that location.
5. As soon as the visual system indicates that the eyes are at the desired location, a command is then issued to the visual system to perceive to move the component to the current eye location.

The advantage of breaking down an instruction into steps is based on the assumption that each step is independent of the current task. Initially, all the task-specific knowledge is in declarative memory and all the task-independent knowledge is also in procedural memory. With time, declarative knowledge is gradually compiled into procedural knowledge which produces task-specific production rules and therefore speeds up the process. Fig. 3 shows the overall goal structure of the model. Based on the design architecture described above, the model could be further developed and translated into computer software. Although this model could be applied to various complex cognitive tasks, some possible shortcomings could include the inability of the participant to control the delay time of the process. This could lead to an increasing rate of bottlenecks which could cause penalties for the participant. Also, the proposed model is a combination of the ACT-R and SOAR theories which both have their individual limitations.

4. Experimental methodology/procedure

The primary objectives are to show that the contemporary theories of skill acquisition could be combined to evaluate complex dynamic cognitive tasks and to show that the proposed ACT-R/SOAR model could be used to predict skill acquisition and accuracy. Twenty-one assembly line workers (14 men and 7 women), ages 18–32 (Mean = 19.86 years, SD = 0.96 years) were randomly selected for this analysis. The participants were all full time assembly line workers at a local computer company. Subjects were tested for any mental or medical disability such as vision impairment or physical disability. The ACT-R/SOAR Software was uploaded on 22 Dell Inspiron 530 with Intel Pentium Dual-core processor E5200 (2 MB L2, 2.5 GHz, 800FSB) – one for each participant and one for control.

Each subject was given an informed consent form which was signed and returned to the researchers before the experiment could be commenced. A demographic sheet concerning previous computer experience and simulations for assembly operations were given to each participant. The subjects were then instructed that the purpose of the study is to examine their accuracy and acquisition of skill based on the simulation of the picking and placing of the PCB components on the assembly flow line over several trials of practice. The necessary ergonomic considerations such as the alignment of the computer table with the seating condition for each participant were made. Other ergonomic factors include the positioning of the keyboard and mouse, and provisions of adequate lighting and ventilation. This experimental study was conducted in a noise proof environment to prevent any external distractions. The participants were then instructed on how to use the necessary key strokes and all other necessary information was provided for easy operation of the computer simulation. All participants were each given a desktop computer so that the test could be conducted at the same time. In order to familiarize themselves with the experiment, participants were allowed to perform two dry tests which were not recorded. The subjects were allowed a short break (2 min) between two trials. For the control experiment, the software was used to develop its own computer participants based on the age and standard deviation information of the human participants.

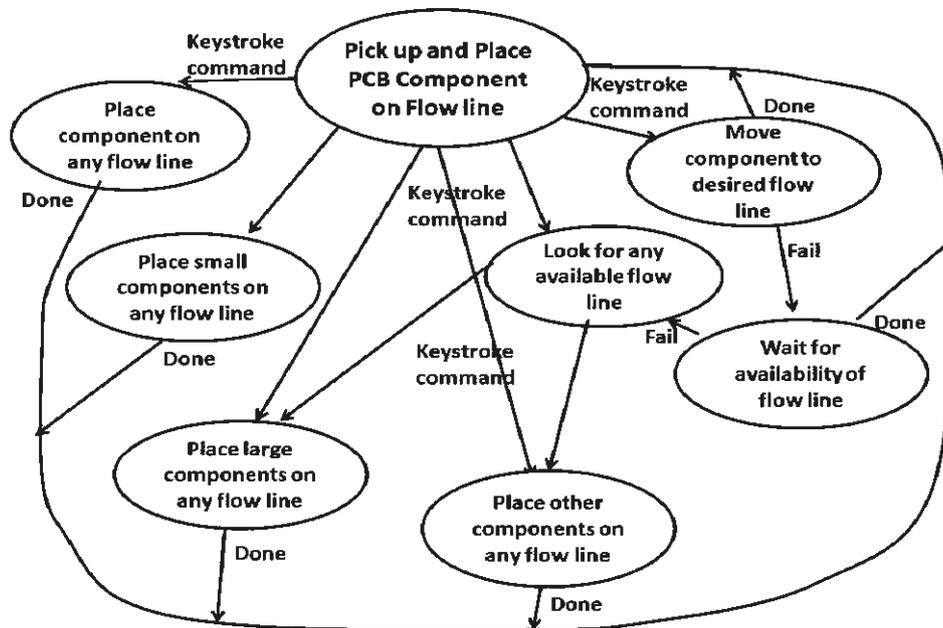


Fig. 3. Structure of the goals.

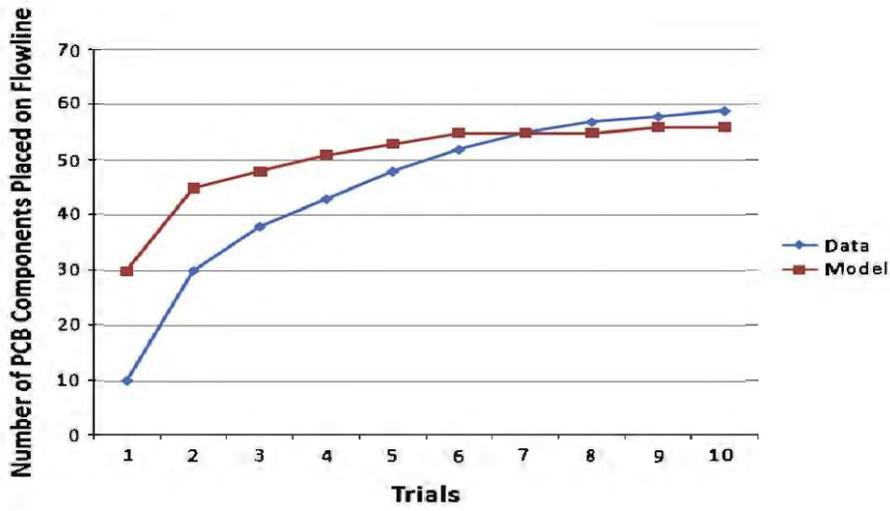


Fig. 4. Number of components placed on flow line by participants and the model.

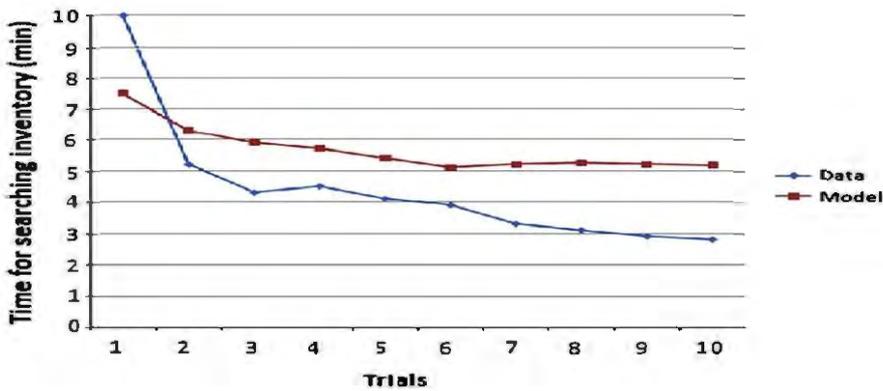
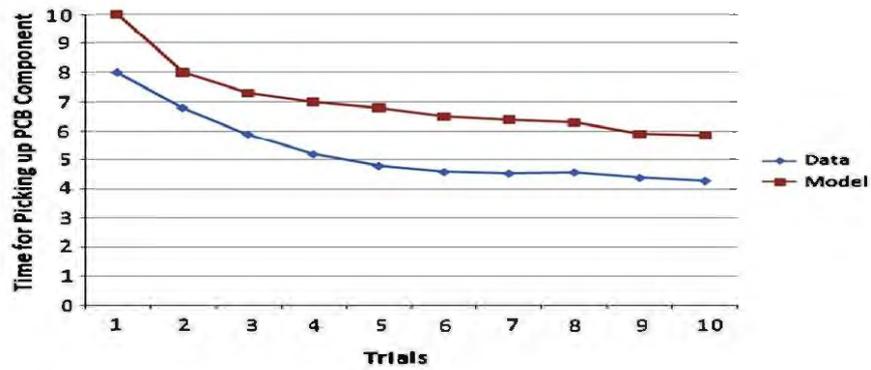
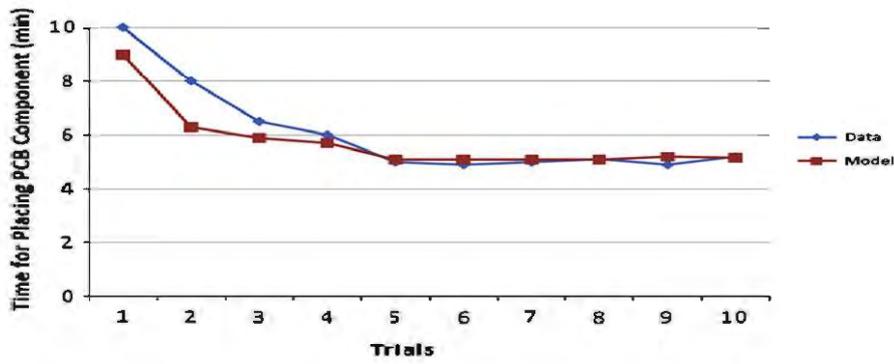


Fig. 5. Unit task performance by participants and the model.

5. Results and discussion

The accuracy and skill acquisition was measured by considering model predictions and the data at three levels: (1) overall performance, (2) unit task level performance, and finally (3) keystroke level performance. In order to obtain accurate model predictions, the model was run three times and results were averaged. All ACT-R parameters were set to their default values.

5.1. Overall performance results

To measure for overall performance, the number of the PCB components picked up and placed within a 10 min trial was measured for the overall performance. Fig. 4 shows the human participants' data and the predictions of the proposed model. At first, the model outperformed the participants by almost a factor of three. However, after a few more trials, the match between the model and data was quite good ($R^2 = 0.94$).

The initial advantage of the model is probably due to the already incorporated declarative knowledge and the availability of all the initial information needed for the task. The human participants still had to gather some additional information before the test. Lee and Anderson (2001) argued that most of the initial speed-up of participants often occurs late since it will naturally take some time to learn the location of all the visual information on the

screen, thereby leading to unnecessary eye movement and response delay. This gave the model an added advantage since it already has the visual locations in the declarative memory. Also, the model begins with some level of efficiency in the strategy of the declarative memory; this could be true for some of the participants but not for all of them.

5.2. Performance at the unit task level

As indicated in the task analysis, three main unit tasks identified are: picking of PCB component and delaying placement, picking and placing of components of the flow line, and inspection of component for quality. Fig. 5 shows the results of the experiment and the model predictions for the time it takes to complete each of the three unit tasks.

It can be seen that the model and the data for the placing activity of the PCB on the flow line unit task was very good ($R^2 = 0.96$), however, the model became slower when compared to the remaining two unit tasks. This is mostly true for the time for moving PCB component unit tasks, where, apart from the first trial, the model is much slower. This mismatch can probably be explained based on two reasons: (1) The strategy used by the model is to check if a flow line is available for placement before attempting to pick the component unit task, therefore, the model may not be able to perform consecutive picking unit tasks without first checking the

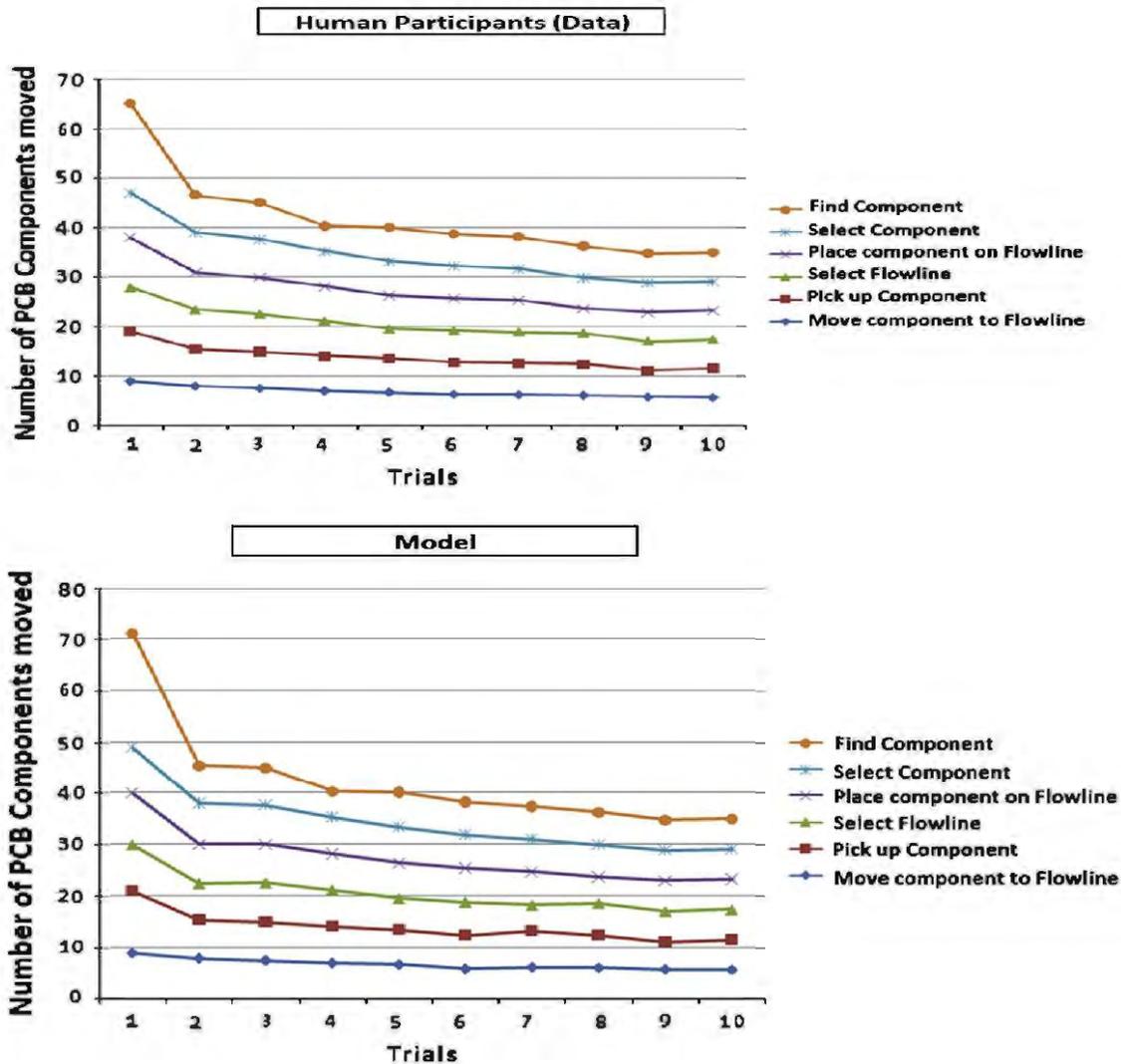


Fig. 6. Keystroke level performance on the number of components placed.

inventory or the delay possibility. (2) The model uses only a few pick unit tasks in each trial. Therefore, restricting its pick time while participants use other strategies, may gain added advantage for this particular unit task. For the inventory search for quality task, trial, the participants are slightly faster than the model ($R^2 = 0.76$). This may again be due to the model incapability of doing only a search for the inventory unit task, especially after checking the other possible options. Overall, the match is quite reasonable since the default ACT-R parameters were used.

5.3. Performance at the keystroke level

In terms of analyzing the performance at the keystroke level, the study was limited to the placement of component unit task since this is assumed to be the most complicated of the unit tasks. The six types of keystroke level goals for the placement of component unit tasks were used (Fig. 2). If these predictions of the model and the performance of the participants are compared, it can be seen that the pattern is the same. This means keystroke times are in the right order, with the slowest keystrokes for the model also being the slowest keystrokes for the participants. The observed learning patterns were also very similar. The major difference between the model and the data is the scale used.

The model is slower, particularly for the more “cognitive” keystrokes like finding and selecting a component. This is due to the fact that the model restricts its ability to make unnecessary keystrokes while human participants do not. This is true since the model already starts out with an accurate representation of what to do in the task while the human participants sometimes still need to find out some more information. Fig. 6 shows the time to complete these keystroke level goals for both the data and the model ($R^2 = 0.68$).

6. Conclusion

This investigation revealed that although the proposed model was able to predict accuracy and skill acquisitions, the model already started out with a complete strategy of performing the task, whereas the human participants had to acquire the information during the trials. This is in accordance with the initial assumption that the model would outpace the subjects indicated in overall performance. This experimental study shows that the contemporary theories of skill acquisition could be combined to evaluate complex dynamic cognitive tasks. It has also been shown that the proposed ACT-R/SOAR model could be used to predict skill acquisition and accuracy. Additional research could be done in other areas of industrial applications such as mining, manufacturing, and service industries. This will provide the opportunity to generalize the proposed model across a wider range of applications. Future investigation could include the incorporation of the ACT-R/SOAR model with one or more other theories of skill acquisition such as the Logan's instance theory which sees improvement in performance as automatic, based on its reliance on the retrieval of past instances. Additionally, efforts will be made to determine the factors that can contribute to enhance the performance of the human subjects to the same level as the model.

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