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A cognitive taxonomy of medical errors

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Abstract

Objective. Propose a cognitive taxonomy of medical errors at the level of individuals and their interactions with technology.

Design. Use cognitive theories of human error and human action to develop the theoretical foundations of the taxonomy, develop the structure of the taxonomy, populate the taxonomy with examples of medical error cases, identify cognitive mechanisms for each category of medical error under the taxonomy, and apply the taxonomy to practical problems.

Measurements. Four criteria were used to evaluate the cognitive taxonomy. The taxonomy should be able (1) to categorize major types of errors at the individual level along cognitive dimensions, (2) to associate each type of error with a specific underlying cognitive mechanism, (3) to describe how and explain why a specific error occurs, and (4) to generate intervention strategies for each type of error.

Results. The proposed cognitive taxonomy largely satisfies the four criteria at a theoretical and conceptual level.

Conclusion. Theoretically, the proposed cognitive taxonomy provides a method to systematically categorize medical errors at the individual level along cognitive dimensions, leads to a better understanding of the underlying cognitive mechanisms of medical errors, and provides a framework that can guide future studies on medical errors. Practically, it provides guidelines for the development of cognitive interventions to decrease medical errors and foundation for the development of medical error reporting system that not only categorizes errors but also identifies problems and helps to generate solutions. To validate this model empirically, we will next be performing systematic experimental studies.

1. Introduction

The medical error report from the Institute of Medicine [1] has greatly increased people's awareness of the frequency, magnitude, complexity, and seriousness of medical errors. As the eighth leading cause of death in the US with as many as 98,000 preventable deaths per year, ahead of deaths due to motor vehicle accidents, breast cancer, or AIDS, medical error has received increased attention from academic, healthcare, and government institutions and organizations. As a result of the report and subsequent increased funding for research from US government and private institutions, many studies on medical errors have been conducted and reported recently (e.g., JAMIA Special Supplement in 2002 [2] and JBI Special Issue in 2003 [3]). There is accordingly an urgent need to develop theoretical foundations to provide insight into the nature of medical errors. Without such foundations it will be difficult to understand the fundamental factors and mechanisms of the problem such that medical errors can be prevented or greatly reduced systematically on a large scale. One of the needed foundations is the cognitive basis of medical errors. The purpose of this article is to propose a taxonomy of medical errors that is based on their cognitive mechanisms. Such a taxonomy will be useful and significant for medical error research and development activities in the medical informatics community, such as identifying targeted categories of medical errors for interventions by designing specific decision-support and other information systems, providing user-interface design guidelines for medical devices and health information systems, providing an ontology for designing

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medical error reporting systems, and providing a structured dataset for the analysis and mining of medical error data.

Why are cognitive factors fundamental in medical errors? Let us first consider the various levels of the healthcare system hierarchy at which medical errors might occur (see Fig. 1). At the core level of the hierarchy, it is individuals who trigger errors, although the individuals may not be the root cause of such errors. Cognitive factors of individuals, such as memory loss, attention switching, deviations in skilled performance and actions, cognitive load, reasoning errors, decision biases and faulty heuristics, etc., play the most critical role here [4–6]. This is traditionally the domain of research for cognitive psychology, cognitive science, and human factors. At the level of Individual-Technology Interaction, errors can occur due to various factors in the interactions between an individual and technology. This is an issue of human–computer interaction where cognitive properties of interactions between a human being and technology affect and sometimes determine human behavior [7–16]. A key challenge for medical error research at this level is to design medical devices and systems in a way that certain medical errors are made impossible by design. At the level of Distributed Systems, errors can be attributed to the social dynamics of interactions between groups of people who interact with complex technology in a distributed cognitive system. This is the issue of distributed cognition, computer-supported cooperative work, and the sociotechnical approach to human-centered design [9,12,14,15,17–24]. A key issue at this level is to understand medical errors that are due to social–technical factors such as information flow, team dynamics, the practice of cognitive work, process reengineering, and cultural and environmental properties. At the level of Organizational Structure, errors can be attributed to factors inherent in organizational structures such as coordination, cooperation, and collaboration among various units; communications, organizational change, organizational memory, group decision making; and the standardization of work processes, skills, and input and output [25–28]. At the Level of Institutional Functions, errors can be indirectly traced back to institutional policies and guidelines [29]. And at the level of National Regulations, errors can be reduced or prevented if systematic and comprehensive requirements such as usability and human factors testing for medical devices are mandated for vendors as a component in the approval process of medical devices [30]. Although the properties at the six levels of the system hierarchy can be studied independently, a cognitive foundation for the system is essential for a comprehensive and in-depth understanding of medical errors across the full span of the hierarchy.

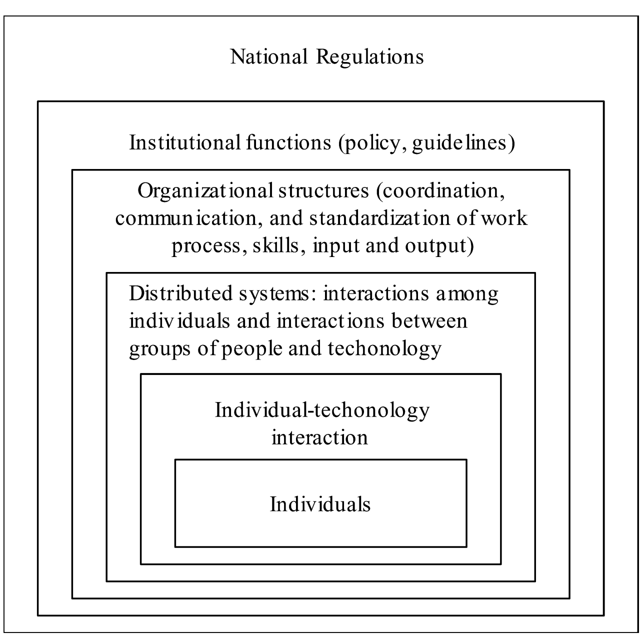

Fig. 1. A system hierarchy that we have devised to illustrate the roles of human errors in medicine.

The importance of cognitive factors in medical errors can also be seen from the perspective of error event chains (see Fig. 2). Consider a typical device use error, found in the FDA's Manufacturer and User Facility Device Experience Database (MAUDE), in which a nurse, trying to program an infusion pump to deliver 130.1 ml/h, presses the keys "1 3 0 . 1" but is unaware that the decimal point on the device only works for numbers up to 99.9. The pump ignored the decimal point key press and, as a result, was programmed to deliver 1301 ml/h. Such errors are typically blamed on the user and "solved" by recommending that the user (or users) be retrained. Unfortunately, this analysis overlooks several important factors that contributed to the error. Why did the decimal point only operate up to 99.9? Why does the device simply ignore the decimal keypress, instead of alerting the user and requiring him or her to reenter the entire number? Why was the device not designed in a way such that it accepts decimal point correctly? Why was the nurse unaware of the limitation? Was training, which is important for a badly designed

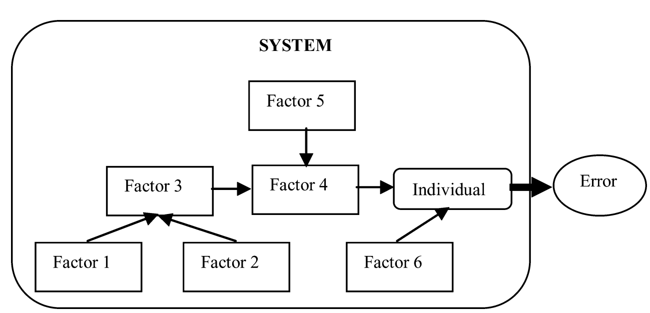

Fig. 2. A schematic drawing of the chain of events leading to an error.

device, inadequate? Was the decimal point limitation covered in training? Why was the order written for 130.1, an amount that the pump was incapable of delivering? Why did the nurse not see that the display showed 1301? Was the display hard to read? Was the device placed at an angle that distorted the display? Was the nurse in a hurry or tired? Was the hospital understaffed? When we consider the full range of factors that may have contributed to the error, it is clear that the individual user who triggered the error is at the last stage of the chain, but may not be the root cause of the error. If the chain of events can be stopped at the individual's stage through interventions, potential errors could be prevented. Even if errors proceed through the last stage, a good understanding of the situation by individuals can help them to recover from the errors and to minimize the potential impact. In the example above, cognitive factors must be considered during device design, device procurement, device programming, training, the clinical environment, and order entry.

Medical errors are often triggered by human errors that occur during the healthcare process as a result of the interplay between human beings and the systems in which they are embedded. According to Reason [1,4], human error is the failure of a planned sequence of mental or physical actions to achieve the intended outcome when this failure cannot be attributed to chance. By this definition, medical error is a cognitive phenomenon because it is an error in human action which is a cognitive activity. To prevent human error, the system in which humans work must be adapted to their cognitive strengths and weaknesses and must be designed to ameliorate the effects of human error that does occur. To design such a system, it is critical to understand the underlying cognitive mechanisms of medical errors.

Although understanding the cognitive basis of medical errors is an important step to reducing adverse events—patient injury resulting from medical management rather than the patient's disease—it is only part of the picture, because not all adverse events are caused by medical errors. For example, a device malfunction, such as an infusion pump that delivers the wrong dose due to a mechanical failure, may lead to an adverse event, but is not a medical error. Adverse events may also arise from system level problems even when all of the individuals working in the system do not make an error. For instance, McNutt et al. [29] describe a case resulting in cardiac arrest due to delays in care caused by organizational policies. There are also non-preventable adverse events. For example, a patient who gets a usual dose of drug may suffer an unpredictable reaction.

The objective of this article is to develop a taxonomy of medical errors that is based on the cognitive factors and mechanisms at the level of Individuals and at the level of Individual-Technology Interaction in the system hierarchy shown in Fig. 1. We acknowledge that many taxonomies can be developed for medical errors for different purposes. For example, medical errors can be categorized according to the levels in the system hierarchy in Fig. 1. This taxonomy is valuable for identifying the factors of medical errors at various levels of the system hierarchy. Medical errors can also be categorized according to different task domains where medical errors occur (e.g., surgery, medication, radiology, diagnosis, etc.). This taxonomy is valuable to identify the frequency and severity of medical errors in each task domain such that special attention can be dedicated. Furthermore, for a sub-category of medical errors, such as medication errors, a detailed taxonomy can be developed to list the various factors for documentation and other purposes [31,32]. The cognitive taxonomy that we develop here serves a purpose that has not been addressed systematically in the medical error research community: describing, understanding, and explaining medical errors. Ideally, we need a meta-taxonomy that is composed of several taxonomies that emphasize different issues and are for different purposes. Such a meta-taxonomy will be important for the interventions of medical errors.

2. Theoretical background

One critical step toward a cognitive foundation of medical errors is to develop a cognitive taxonomy of medical errors that can (1) categorize major types of medical errors along cognitive dimensions, (2) associate each type of medical error with a specific underlying cognitive mechanism, (3) describe how and explain why a specific error occurs, and (4) generate intervention strategies for each type of error.

The purpose of this paper is to propose an action based cognitive taxonomy that can potentially satisfy the four criteria listed above. This taxonomy is built upon two theoretical grounds: Reason's definition of human error [4] and Norman's action theory [10,33]. We describe these two theoretical perspectives first.

2.1. *Reason's definition of human error*

Reason's [4] definition of human error is one of the most widely accepted: an error is a failure of achieving the intended outcome in a planned sequence of mental or physical activities when that failure is not due to chance. According to Reason, human errors are divided into two major categories: (1) slips that result from the incorrect execution of a correct action sequence and (2) mistakes that result from the correct execution of an incorrect action sequence. Slips have been extensively studied and are better understood (for reviews, see [4,5]). In comparison, there have not been as many studies of mistakes.

2.2. Norman's action theory

To be comprehensive, descriptive, predictive, and generalizable, a cognitive taxonomy should be based on a cognitive theory that has explanatory and predictive power. Since human errors are defined as errors in human actions, a cognitive theory of human actions can provide the theoretical foundation for the cognitive taxonomy. A cognitive theory of human action that is particularly pertinent for understanding the nature of medical errors is the seven-stage action theory developed by Norman [10,33] and refined by Zhang and colleagues [34,35]. The seven-stage action theory is shown in Fig. 3, with an example showing the action cycle of entering the volume of drug to be infused with an infusion pump. According to this theory, any action has seven stages of activities: (1) establishing the goal (e.g., "set volume to be infused at 1000 cc"), which is abstract and independent of the system or concrete setting; (2) forming the intention (e.g., "use keypad to enter 1000"), which is concrete and dependent on the actual system or concrete setting; (3) specifying the action specification (e.g., "press 1 0 0 0"), which is the formation of the sequence of actions to be carried out; (4) executing the action (e.g., "physically pressing 1 0 0 0"), which is physically carrying out the actions; (5) perceiving the system state (e.g., "volume: 1000 cc, with 1000 highlighted"), which is to detect and recognize any changes in system state; (6) interpreting the state, which means to make sense of the information perceived from the perception stage (e.g., "1000 cc is displayed, but what does the highlighting mean? Has the pump accepted the value, or must I press another button?"); and (7) evaluating the system state with respect to the goals and intentions (e.g., "determine if the system has accepted the volume, i.e., press key to start infusion"), which is to check if the original goal has been completed.

It is worthwhile to describe the difference between goals and intentions. Goals are typically high level objectives that are abstract and independent of the system or concrete setting. In the example in Fig. 3, "set volume to be infused at 1000 cc" could be implemented in different ways, depending on the actual system being used. For infusion pumps with a keypad, as in Fig. 3, it is carried out by typing the numbers. For other infusion pumps, it is done by using up–down arrow keys to increment or decrement a displayed value, and some pumps support both means of entry. Intentions are instantiated goals in a specific system or setting. In the example in Fig. 3, the intention is "use keypad." In a pump without a keyboard, the intention may be "press up arrow." Intention has more details than goals.

The action cycle in Fig. 3 embodies a simple task that has no subgoals or represents one of the levels of a complex task that has subgoals. The complete action diagram for a complex task with several levels of subgoals will include many nested action cycles. To limit our scope for this discussion, we use the action cycle of a simple, one-level task to develop our taxonomy.

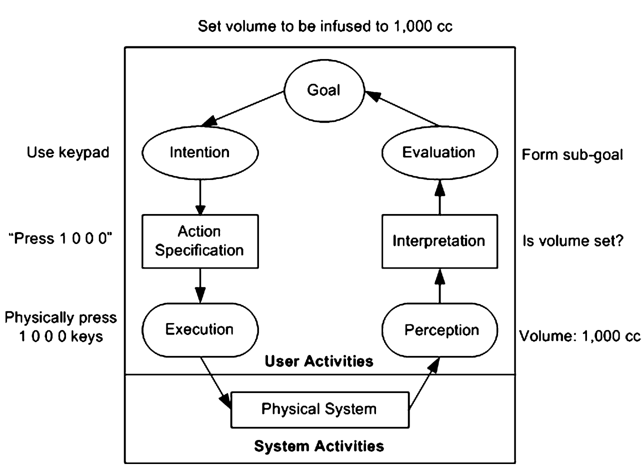

Fig. 3. Norman's seven-stage theory of action.

3. The cognitive taxonomy

Reason developed one of the most well-known taxonomies of human errors [4]. However, it was not based on a theory of human action. It focused primarily on slips, not on mistakes; and it has not been systematically applied to medical settings. Norman's [33] seven-stage action theory was developed for the study of human–computer interaction and the design of user interfaces. It has not been applied to the study of human errors.

The cognitive taxonomy we propose here adopts Reason's definition of human error and his basic categorization of human errors into slips and mistakes. Our taxonomy is also an application and extension of Norman's action theory to the categorization of medical errors. It is an action-based cognitive taxonomy. This taxonomy can cover major types of human errors, because a human error is an error in an action and any action goes through the seven stages of the action cycle.

In our taxonomy, errors (both slips and mistakes) can occur at any of the seven stages of action: due to incorrect translation from goals to intentions, incorrect action specifications from intentions, incorrect execution of actions, misperception of system state, misinterpretation of data perceived, and misevaluation of interpreted information with regard to the goal of the task. We extend Reason's definition of an "action sequence" to include steps on the evaluation side as well as the execution side of the action cycle. According to Reason's definition a slip is an incorrect execution of a correct action sequence, whereas a mistake is the correct execution of an incorrect action sequence. In our model, these actions include steps on the evaluation side of the action cycle (see right-hand side of the cycle in Fig. 3). For example, misinterpreting feedback because of expectations (e.g., reading 1301 as the expected 130.1) is a slip, whereas misinterpreting feedback because of incorrectly acquired or missing knowledge (e.g., thinking that a blinking red light means the device is working, when in reality it means the battery is low) is a mistake.

It may help to think about slips and mistakes in the context of the competence–performance distinction, first used by Chomsky [36] to characterize the difference between linguistic competence (a person's tacit knowledge of a grammar) and linguistic performance (that a person often produces sentences inconsistent with their grammatical knowledge). In the context of medical errors, competence refers to a person's knowledge of how to perform a task or process, or how a device must be operated. This knowledge may be correct, incorrect, or incomplete. Performance describes a person's actual behavior. When behavior leads to a failure because of incorrect or incomplete knowledge, we call this a mistake. When the knowledge is correct, but a failure occurs, we call this a slip. For example, we all know the difference between a computer mouse and a cell phone, but if a mouse and cell phone are next to each other on our desks, we may accidentally pick up the mouse when the phone rings or we may accidentally reach for the phone when we want to move the mouse—both examples of a slip. In contrast, a mistake involves missing or incorrect knowledge.

3.1. Slips

Under our cognitive taxonomy, slips can be divided into execution slips and evaluation slips (see Fig. 4 and Table 1).

3.1.1. Execution slips

Execution slips are associated with the execution of an action. They occur at stages of Goal, Intention, Action Specification, and Execution.

3.1.1.1. Goal slips. Goal slips can be caused by many cognitive mechanisms. In human memory, a goal may be forgotten because of high memory load, delays, or interruptions (loss of activation). A correct goal could be distorted because of its similarity to a more common goal. For an activity that has multiple tasks occurring concurrently or sequentially, the goals for different tasks can be mixed up (concurrent and sequential cross talk). For an activity with multiple tasks, the goals for some of the tasks may get lost because the goals are too numerous to be kept in working memory (overflow of goal stacks). In the goal slip example in Table 1, the goal of "seeing patient A" is forgotten and the doctor moves to the goal of "seeing patient B." This is an example of loss of activation.

3.1.1.2. Intention slips. Similar to goal slips, intention slips can also be caused by loss of activation, altered intention, concurrent and sequential cross talks, and overflow of working memory. A goal is at the level of the user's task and is independent of the device or tool being used, whereas an intention is a goal tied to the specific features or functions of the device. For instance, if your goal were to view the next page of a document, you would intend to turn the page of a written document or scroll to the next page of an electronic document. In each case, the intention is tied to the tool you are using, whereas the goal is independent of the tool. In the intention slip example in Table 1, the intention was to enter the infusion pump rate using the up–down arrow keys. This technique is required on the most frequently used pumps. However, on the present device the arrow keys move the highlighted selection region, instead of changing the selected number. Although the nurse knew this, the more common intention was retrieved instead. This is a capture slip: a well-learned intention is retrieved instead of the correct intention.

3.1.1.3. Action specification slips. Action specification slips can be caused by associative activation, description,

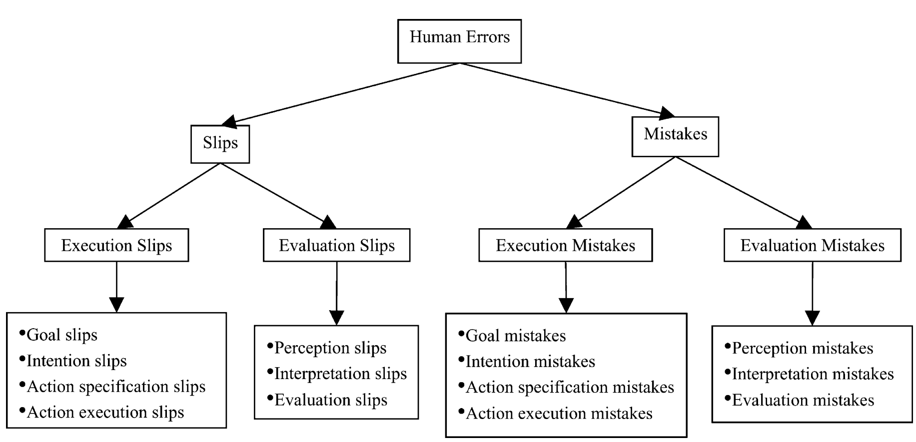

Fig. 4. Proposed cognitive taxonomy of medical errors.

Table 1
Slips

	Stage in action cycle	Examples	Cognitive mechanisms	Potential solutions
Execution slips	Goal slips	A doctor was called out of the room to answer an urgent call and afterwards he went to the room of a different patient who was next in the queue. (Loss of activation)	• Loss of activation • Cross talk (concurrent) • Cross talk (sequential) • Altered goal • Overflow of working memory	• Provide memory aids • Reduce multitasking • Reduce interruptions • Reduce goal stacks • Train users
	Intention slips	A nurse intended to enter the rate of infusion using the up–down arrow keys, because this is the technique required on the pump she most frequently uses; however, on this pump the arrow keys move the selection region instead of changing the selected number. (Capture)	• Loss of activation • Cross talk (concurrent) • Cross talk (sequential) • Altered intention • Overflow of working memory	• Provide memory aids • Reduce multitasking • Situated actions • Reduce interruptions
	Action specification slips	A nurse intends to decrease a value using the decrement function, but pushes the down arrow key (which moves to the next field) instead of the minus key. (Associative activation)	• Associative activation • Description • Failure of retrieval • Situated activation • Cross talks	• Automation • Decision support • Situated actions • Train users • Direct action
	Action execution slips	"I meant to turn off the antibiotics IV only, but turned off the infusion pump completely." (Double capture)	• Capture • Double capture • Perceptual confusion • Deviation of motor skills • Misfiring	• Automation • Visualization • Display design • Reduce interruption • Memory aids
Evaluation Slips	Perception Slips	A patient died of liquid aspiration because the water trap connected with a tube had no mechanism to protect against reflux to patient's trachea, and there was no feedback in the system. (Lack of perception)	• Lack of perception • Misperception • Mis-anticipation	• Direct perception • Immediate feedback
	Interpretation Slips	A yellow flashing light on a medical device was interpreted as non-critical when it really meant critical. (default knowledge)	• Default knowledge • Confirmation bias • Information overload	• Display design • Decision support • User training • Memory aids • Situation awareness
	Action evaluation slips	A user pressed the start button on an infusion pump after which the pump indicated that it had started infusing, so the user assumed the patient was receiving the drug; however, the user had forgotten to open the clamp on the hose, so no drug was being delivered to the patient.	• Lost memory of goal • Lack of feedback • Insufficient information • Ambiguous information • Evaluating different goal	• Memory aids • Display design • Action tracking • Information reduction

failure of retrieval, situated activation, and cross talk. The action specification slip example in Table 1 is caused by associative activation, which is the activation of similar but incorrect knowledge. In this case, a nurse intended to decrease the volume to be infused by using the decrement key of the device, rather than keying in the new value. The nurse immediately thought to press the down arrow button and correctly executed this command and then noticed that this moved the highlighted line from volume to be infused to rate. The nurse knew that he should have pressed the minus key instead, but associative activation of similar knowledge, namely that down arrows are often used to decrement numbers, led to an action specification slip. In this example, the intention (use the decrement key) was correct, but the specification was incorrect. In contrast, in the intention slip example described previously the intention itself was incorrect. A description slip [5] is another type of action specification slip, which is an incomplete or ambiguous specification of an intended action that is similar to a familiar action. Failure of retrieval of a well-learned action sequence can also result in an action specification slip. Sometimes a strong environmental stimulus can automatically and unconsciously activate an action that replaces the current intended action. When multiple tasks are performed concurrently or sequentially, there is always the possibility of cross talk between the action components of the tasks.

3.1.1.4. Action execution slips. In the actual execution of a correctly specified action sequence, slips could occur due to capture and double capture [4,5], perceptual confusion, deviation of motor skills, misfiring of actions, and other mechanisms. A capture slip is the automatic activation of a well-learned routine that overrides the current intended activity. For example, an intended action of "taking a medication with milk" can be overridden by "drinking milk alone," which is a stronger routine action. A double capture slip is the unintended activation of a related strong action routine. The action execution slip example in Table 1 is a double capture slip. In this case, the intended action "turning off the antibiotics IV is overridden by "turning off the infusion pump completely," which is an unintended related routine. Action execution slips can also be caused by perceptual confusion (e.g., misreading of a handwritten prescription), deviation of motor skills (e.g., typos in the typing of radiology report), misfiring of action rules (e.g., due to the superficial match of the conditions for certain actions), and other mechanisms.

3.1.2. Evaluation slips

Evaluation slips are associated with the evaluation of the outcomes of an action. They occur at the stages of Perception, Interpretation, and Action Evaluation.

3.1.2.1. Perception slips. Perception slips can be caused by lack of perception, misperception, and mis-anticipation. The perception slip example in Table 1 is caused by lack of perception. In this case, there was no display, either auditory or visual, of the current state of the system. To get the information about the erroneous state of the system, one had to infer it by looking at and comparing the level of the patient and the level of the system. Misperception is another source of perception slips. It is the incorrect perception of correction information. This could be caused by many factors such as environmental conditions (e.g., light and noise) or the displays or systems themselves (e.g., hard to read text and hard to hear signals). Mis-anticipation can also cause perception slips. In this case, the perception of the outcome of an action may be distorted and biased by the anticipation of a specific outcome even if the actual outcome turns out to be different from the anticipated outcome.

3.1.2.2. Interpretation slips. Interpretation slips can be caused by different factors, such as default knowledge, confirmation bias, and information overload. The interpretation slip example in Table 1 was caused by default knowledge, which fills unknown variables in the knowledge structure with default values. Typically, a red warning light, not a yellow warning light, indicates a critical situation that needs immediate attention. In this specific case, the yellow light was designed to indicate a critical situation. The operator had this knowledge but unfortunately interpreted it using the default meaning of a yellow light (non-critical). Confirmation bias is the tendency to interpret the outcome as a piece of confirming, positive, or consistent evidence for one's hypothesis or anticipation. Thus, an outcome incompatible with the goal might be misinterpreted as one that indicates the completion of the goal. Information overload is another factor that could cause misinterpretation or incomplete interpretation of the outcome of an action. In this case, the information of the outcome might need a lot of processing before becoming interpretable, or it might be buried in a complex array of information resources.

3.1.2.3. Action evaluation slips. Action evaluation slips could be caused by the loss of the memory of the original goal of the task. In this case the evaluation cannot be performed because there is no goal to be evaluated. Insufficient or ambiguous information for evaluation may sometimes force the operator to make a decision to either confirm or disconfirm the completion of the original goal of a task, which could lead to errors. In a multi-task environment, multiple evaluations of multiple goals could be mixed up: an evaluation might be performed for a different goal. The evaluation slip example in Table 1 was caused by the inappropriate activation of knowledge. To achieve the goal of starting infusion therapy, the user normally opens a roller clamp on the IV tubing, and then presses the start button on the infusion pump. In this case, the user forgot to open the clamp and pressed start, causing the pump to indicate that it was beginning to infuse—action feedback that the user evaluated as meeting the goal of starting the infusion.

3.2. Mistakes

In comparison with slips, there have been much fewer studies on mistakes in medicine, probably due to the complexity and depth of domain knowledge that is required to understand and study mistakes in medicine. Most studies about mistakes in the past were byproducts of studies of reasoning biases and heuristics in decision-making tasks [37,38]. Recently there has been a growing number of studies that explicitly examine various types of mistakes in medicine [39–41]. We expect to see more studies of this kind. Here we only describe the basic categories of mistakes under our taxonomy. However, the framework of our taxonomy allows accommodating new data and theories as they become available.

Under our cognitive taxonomy, mistakes are categorized into execution mistakes and evaluation mistakes (see Fig. 4 and Table 2).

Table 2
Mistakes

	Stage in action cycle	Examples	Cognitive Mechanisms	Potential solutions
Execution mistakes	Goal mistakes	Incorrect diagnosis due to neglect of base rate information. (Biases)	• Incorrect knowledge • Incomplete knowledge • Misuse of knowledge • Biases & faulty heuristics • Information overload	• Education • Decision support • Representational aid
	Intention mistakes	A physician treating a patient with oxygen set the flow control knob between 1 and 2 liters per minute, not realizing that the scale numbers represented discrete, rather than continuous, settings. (Incomplete knowledge)	• Incorrect knowledge • Incomplete knowledge • Misuse of knowledge • Biases • Faulty heuristics • Information overload	• Education • Decision support • Representational aid • Information reduction • Display design
	Action specification mistakes	Strange burn scars appeared in post-operative patients in a hospital. The problem was caused by electric discharge of a device that was not grounded. The device has a blinking red light to signal the problem, but the device operators did not know the meaning of the signal. (Incomplete knowledge)	• Lack of correct rules • Misfiring of good rules • Encoding deficiencies in rules	• Education • Decision support • Representational aid
	Action execution mistakes	For example, a perfect knowledge of a surgical procedure may not lead to a successful surgical operation if the operator has not extensively practiced the procedure. (Dissociation between knowledge and rules)	• Misapplication of good rules • Dissociation between knowledge and rules	• Education • Representational aid • Automation
Evaluation mistakes	Perception mistakes	A pharmacist filling prescription for Lamisil (an antifungal) mistakenly perceived Lamictal (an anticonvulsant) as Lamisil because he mistakenly expected of looking for Lamisil. (Misperception)	• Lack of perception • Misperception • Mis-anticipation	• Aids for perceptual systems • Display design
	Interpretation mistakes	A steady green light on an infusion pump means the device is ready, and a flashing green light indicates an infusion is in progress. The device user did not know the meaning of the steady green light, and incorrectly interpreted it as an indication that the infusion had begun. (Incorrect knowledge)	• Incorrect knowledge • Incomplete knowledge • Information overload	• Education • Representational aid • Information reduction • Display design
	Action evaluation mistakes	In the infusion pump example shown in Fig. 3, the user may not know that the device has accepted the volume, and may then assume that the goal ("set volume to be infused at 1000 cc") has not been accomplished, leading to a search for additional buttons (such as "enter") to complete the goal. (Incomplete knowledge)	• Incorrect knowledge • Incomplete knowledge • Information overload	• Education • Representational aid • Information reduction • Display design

3.2.1. Execution mistakes

Like execution slips, execution mistakes can occur at the stages of goal, intention, action specification, and action execution. These correspond to the first four stages in the action cycle. Goal mistakes and intention mistakes are mistakes about declarative knowledge, which is knowledge about factual statements and propositions, such as "Motrin is a pain reliever and fever reducer." Action specification mistakes and action execution mistakes are mistakes about procedural knowledge, which is knowledge about procedures and rules, such as "give 1 tsp Motrin to a child per dosage up to four times a day if the child has fever or toothache and the weight of the child is 24–35 lbs."

3.2.1.1. Goal mistakes. Goal mistakes are basically incorrect goals set by some means. They can be caused by many complex factors such as incorrect knowledge, incomplete knowledge, misuse of knowledge, biases and faulty heuristics, information overload, etc. For example, neglect of base rate information could result in incorrect diagnosis of a disease. This is a well-documented finding in human decision making tasks [37,38]. As another example, the goal of "treating the disease as pneumonia'' could be a mistake if it is a misdiagnosis based on incomplete knowledge (e.g., without X-ray images).

3.2.1.2. Intention mistakes. Given a correct goal, the intention of how to achieve the goal could be incorrect, due to similar factors for goal mistakes. The intention mistake example in Table 2 was due to incomplete knowledge. The goal of giving oxygen between 1 and 2 liters per minute was correct. However, the intention of setting the knob between 1 and 2 was incorrect because the physician did not have the knowledge that the scale numbers on this specific device only represent discrete, not continuous, settings [30].

3.2.1.3. Action specification mistakes. Action specification mistakes are procedural mistakes that can be caused by many factors such as lack of correct rules, over generalized application of good rules, and encoding deficiencies in rules. The example in Table 2 is due to the lack of correct rules: ''if the red signal is blinking, ground the device's electrical system.'' The operator in this case did not have this rule. Procedural mistakes can also be caused by over generalized application of good rules. In this case, the condition part of a condition–action rule could be misidentified and mismatched, thus causing the firing of the action part of the rule. Procedural mistakes caused by encoding efficiencies of action rules are usually due to the evolving nature of the rules and unforeseeable conditions that cannot be encoded in the rules.

3.2.1.4. Action execution mistakes. Action execution mistakes can be caused by misapplication of good rules and the dissociation between knowledge and rules. A good rule may be misused because the user may have incorrect or incomplete knowledge about the condition of the rule in a specific context. The knowledge of a rule and the knowledge of how to use a rule are not always automatically linked together without extensive practice. This dissociation, due to the lack of experience and practiced skills, may also lead to action execution mistakes. A good recipe may not lead to a good dish. For example, perfect knowledge of a surgical procedure may not lead to a successful surgical operation if the operator has not extensively practiced the procedure.

3.2.2. Evaluation mistakes

Evaluation mistakes occur at the stages of Perception, Interpretation, and Evaluation on the evaluation side of the action cycle.

3.2.2.1. Perception mistakes. Perception mistakes can be caused by expectation-driven processing. What we perceive is a function of the input and our expectations. This is what allows us to read sloppy handwriting, or recognize degraded images. However, our expectations can also lead to misperceptions. For instance, a pharmacist filling prescription for Lamisil (an antifungal) mistakenly perceived Lamictal (an anticonvulsant) as Lamisil. In this case the pharmacist clearly knows the desired drug and is capable of correctly reading Lamictal, but the expectation of looking for Lamisil resulted in a perception mistake. Perception mistake can also occur in the process of diagnosis. For example, a strong anticipation of a specific diagnosis may lead to misperception of an X-ray image.

3.2.2.2. Interpretation mistakes. Interpretation mistakes are the incorrect interpretation of feedback caused by incorrect or incomplete knowledge. For instance, suppose that an infusion pump indicates readiness to begin infusion using a steady green light and that the infusion is in progress by flashing the green light. If the device user does not know the meaning of the steady green light, he or she may incorrectly interpret it as an indication that the infusion has begun (an interpretation mistake). In contrast, if a person is familiar with two pumps that each give a different meaning to a steady green light, then erroneously interpreting the light on Pump A as if it were on Pump B is an interpretation *slip*—the user knows the correct interpretation, but familiarity with two inconsistent device interfaces leads to the wrong interpretation.

3.2.2.3. Action evaluation mistakes. An action evaluation mistake occurs when incorrect knowledge or incomplete knowledge leads a person to erroneously judge the completion or incompletion of a goal. In the infusion pump example (Fig. 3), the user may not know that the device has accepted the volume, and may then assume that the goal (''set volume to be infused at 1000 cc'') has not been accomplished, leading to a search for additional buttons (such as ''enter'') to complete the goal.

3.3. Implications of the taxonomy

The cognitive taxonomy we just described, although still preliminary, offers a systematic and theory-based approach to the categorization of medical errors along cognitive dimensions at the level of individuals and their interactions with technology. It associates each type of error with a specific set of underlying cognitive mechanisms that offer possible cognitive explanations for why and how a specific error occurs. With further development and refinement, which will require substantial theoretical and empirical work, it may become a theory with predictive power.

Besides the above theoretical implications, the cognitive taxonomy has at least two implications for applications: the development of cognitive interventions and the design of medical error reporting systems.

3.3.1. Cognitive interventions

The cognitive taxonomy directly offers strategies, methods, and guidelines for the development of cognitive interventions. With the identification of the cognitive mechanisms underlying a specific type of error, we can use our knowledge and understanding of the mechanisms to design cognitive interventions in terms of redesigning the system, restructuring the organization, and re-educating the users. Although the cognitive taxonomy cannot provide the details of each cognitive intervention, it offers general principles and guidelines. In the rightmost columns of Tables 1 and 2, we listed high level guidelines for cognitive interventions. For example, if an error is identified as an intention slip due to the loss of activation in memory, a memory aid should be introduced to address the memory loss problem. An infusion pump might display a message such as "Press Volume to enter volume to be infused." As another example, if an error is identified as an action specification mistake due to the lack of correct rules, re-educating the user is required. This could also be done by redesigning a device, and this is often a better choice. For instance, when using pumps with set-based free flow protection, nurses no longer have to remember to close the clamp. The device has been redesigned to eliminate the need for the rule. Our cognitive taxonomy currently offers only a starting point for the development of cognitive interventions. More studies are required to populate the taxonomy with more cases, to refine the theoretical foundation, and to generate more detailed guidelines for cognitive interventions. These studies are currently under way in our research laboratories. We are conducting field studies to identify types of errors and the conditions under which such errors occur. The results from these naturalistic studies will provide another dimension to our taxonomy, where real-life constraints such as time pressure, stress, and socio-cultural factors play a large role in potential error management [42]. This way, we hope to capitalize from both, laboratory-based carefully conducted heuristic evaluation as well as the ethnographic and observational studies in the naturalistic environment [43].

3.3.2. Medical error reporting system

Another practical implication of our cognitive taxonomy is that it can provide systematic, principled methods for the design of medical error reporting systems. Current systems for this purpose are based mostly on free text in an unstructured format. Medical error data collected in this way are rarely useful for the detection of patterns, discovery of underlying factors, and generation of solutions, because user-entered free text does not contain the types of information needed to propose interventions and it is difficult to analyze in a systematic way. Error reporting systems that do provide coding schemes are often based on domain- or task-specific error types. For example, the NCC MERP medication error taxonomy includes codes for "Improper dose resulting in over dosage" and "Computer error due to incorrect selection from a list by computer operator." [32]. Domain specific taxonomies, such as this one, allow us to analyze and discover error patterns in specific care processes; however, they do not capture the cognitive factors contributing to the error or provide enough information to reasonably infer the role of cognitive factors. For example, in the NCC MERP taxonomy, cognitive factors can be coded only as "Performance Deficit" or "Knowledge Deficit" [31].

Medical error reporting systems should not be merely record keeping systems. They should be systems for the identification of problems and generation of solutions. We are currently in the process of designing an online medical error reporting system that is based on our cognitive taxonomy. In this system, questions and inquiries will be generated to encode cognitively relevant information; the categorization of errors will be along relevant cognitive dimensions; and it will be designed to generate immediate recommendations on possible intervention strategies.

4. Conclusion

One critical step toward reducing medical errors in particular and human errors in general is a cognitive taxonomy of errors that can (1) categorize major types of medical errors along cognitive dimensions, (2) associate each type of medical errors to a specific underlying cognitive mechanism, (3) describe how and explain why a specific error occurs, and (4) generate intervention strategies for each type of error. Based on Reason's [4] definition of human errors and Norman's [33] cognitive theory of human action, we have developed a preliminary action-based cognitive taxonomy of medical errors that more or less satisfies these four criteria. Our taxonomy can categorize major types of errors (slips and mistakes) according to the stages of the action cycle. We have identified a set of cognitive mechanisms (substantial but not exhaustive) that underlie each type of slip or mistake. Our taxonomy can also explain why and describe how a specific error occurs. With future developments we intend that our taxonomy will have enough predictive power to help designers and implementers to anticipate more effectively when and where an error might occur. Finally, at a high, conceptual level, we have generated guidelines for the development of cognitive interventions and have proposed a framework for the development of medical error reporting systems that over time can provide solutions or enhance prevention of the kinds of errors that are reported.

Different taxonomies of medical errors can be developed for different purposes. The cognitive taxonomy we developed here is for the purpose of describing, understanding, explaining, and potentially predicting medical errors by considering the cognitive factors in medical errors. We believe that these cognitive factors are fundamental to medial errors.

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