

The Human Interface of Biomedical Informatics

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Received: 15 June 2018

Accepted: 06 August 2018

Published: 06 September 2018

Abstract

Biomedical informatics is the science of information, where information is defined as data with meaning. This definition identifies a fundamental challenge for informaticians: connecting with the healthcare team by enabling the acquisition, retrieval, and processing of information within the cognitive capabilities of the human brain. Informaticians can become aware of the constraints involved with cognitive processing and with workplace factors that impact how information is acquired and used to facilitate an improved user interface providing information to healthcare teams. Constraints affecting persons in the work environment include as follows: (1) cognitive processing of information; (2) cognitive load and memory capacity; (3) stress-affecting cognition; (4) cognitive distraction, attention, and multitasking; (5) cognitive bias and flexibility; (6) communication barriers; and (7) workplace environment. The human brain has a finite cognitive load capacity for processing new information. Short-term memory has limited throughput for processing of new informational items, while long-term memory supplies immediate simultaneous access to multiple informational items. Visual long-term memories can be extensive and detailed. Attention may be task dependent and highly variable among persons and requires maintaining control over distracting information. Multitasking reduces the effectiveness of working memory applied to each task. Transfer of information from person to person, or machine to person, is subject to cognitive bias and environmental stressors. High-stress levels increase emotional arousal to reduce memory formation and retrieval. The workplace environment can impact cognitive processes and stress, so maintaining civility augments cognitive abilities. Examples of human-computer interfaces employing principles of cognitive informatics inform design of systems to enhance the user interface.

Keywords: Attention, cognitive processing, informatics, memory, stress

INTRODUCTION

Human cognitive abilities play a key role in the reception, memory, and usage of information we manage and disseminate. The number and speed of workplace tasks affects the time available for meaningful communication and interaction with others. People react to the data and services we provide, and how we interface with others can greatly influence the ultimate success of our efforts toward problem solving and decision-making. How we cope with stresses affects our ability to perform our job. The following review addresses multiple aspects of cognition, communication, and stress affecting information behavior in the workplace environment.

COGNITIVE PROCESSING OF INFORMATION

Information behavior includes both active and passive information seeking and information use, may be modified by cognitive processes and requires human manipulation of data

elements. Information must go into and come out of a human brain. How the human brain acquires, processes, and retains information affects the usage of available data.^[1]

Balis described the concept of cognitive processing with information acquisition in the context of “Maxwell’s Demon.”^[2] James Clerk Maxwell, a 19th-century mathematician and physicist, described this mythical creature that strives to increase the order of a system (thus decreasing entropy) without a concomitant increase in total net entropy (disorder). However, this defies the second law of thermodynamics, a fundamental law of physics, which states that entropy in a system must increase. Although orders can be increased in one place for a short period,

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How to cite this article: Klatt EC. The human interface of biomedical informatics. J Pathol Inform 2018;9:30.

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10.4103/jpi.jpi_39_18

the disorder must also eventually increase.^[3] The principle of net entropy applies to learn and memory because the brain operates through rate-limited biochemical and electrochemical functions subject to the laws of physics. Learning requires modification of synaptic interfaces at the neuronal dendritic level.^[4] There are cell- and tissue-based regulatory pathways for learning that are subject to protein synthesis.^[5]

Long-term potentiation (LTP) is the process which underlies forming memory and requires synaptic modification in which a long-lasting enhancement occurs with repetitive stimulation of excitatory synapses. LTP is a biochemical process originating in the paleocortical hippocampus and mediated by N-methyl-D-aspartate (NMDA) receptors.^[6] LTP is actively dependent upon the coincident firing of pairs of neurons. A single neuron will undergo depolarization without activation of NMDA receptors and subsequent protein synthesis. With coincident firing, NMDA receptor-dependent LTP leads to structural changes that show little sign of degradation with time. This synaptic consolidation with structural neuronal changes yields more stable memory.^[7]

The important paleocortical regions involved with short-term memory are medial temporal lobe structures that include the hippocampus, amygdala, and adjacent entorhinal cortex.^[8] LTP has an early phase of 1–3 h not requiring new protein synthesis and a late phase of up to 24 h with changes in gene transcription and protein synthesis. Recall and review of information during these time periods aid LTP. The memories stored in the neocortex eventually become independent of the medial temporal lobe system.^[9]

There is a finite learning rate that is bounded by entropy-driven molecular processes, and this cannot be exceeded, just as Maxwell's demon cannot create order without simultaneously creating disorder. Optimal learning with information acquisition occurs when increasing order (decreased entropy) in the brain happens over a short time so that overall disorder (increased entropy) is also allowed to occur. Increased entropy comes in the form of less intense mental activities including socializing, recreation, and sleep. The effective time for initial information retention in learning is 20 min.^[10] The deterministic aspect of learning indicates how much information can be retained. For learning to occur, only a finite number of synaptic modifications can be established per unit time. These synaptic modifications cannot be increased by increasing the rate of information delivery.^[11] The stochastic aspect of learning involves a decay of learning over time. However, the loss of learned data elements is random, just like another stochastic process: radioactive decay. One cannot tell precisely what data will be lost over time, but some loss will inevitably occur.^[12]

Healthcare professionals may try to improve information storage as memory, and this is possible because over time memories typically become less episodic (highly detailed and specific) and more semantic (more broad and generalized) as the information is repeatedly retrieved and reencoded in workplace contexts supporting LTP. Maintenance of LTP is an active process dependent on the continued protein synthesis.

The act of retrieving and reactivating a memory is thought to put that memory and the potentiated synapses in memory into a labile state, from which it must restabilize to persist. Without this process, known as reconsolidation (requiring protein synthesis), the information in memory can be lost.^[7] Review of information in the learning process can reduce the stochastic process to facilitate LTP with the long-term retention of information and diminish the loss of information.^[9]

In the realm of courtroom proceedings, eyewitness accounts of events may be considered highly accurate. In a study of immediate cued-recall, free recall or no recall, participants watching a crime video, then discussed the video with a confederate who introduced both correct and incorrect information about the video. Accuracy and amount of recall were tested 1 week later. It was found that the immediate-recall questionnaire did not make participants more susceptible to misinformation in comparison to no-recall participants, suggesting that immediate-recall inoculated participants against misinformation. Furthermore, the provision of correct postevent information increased memory accuracy, especially after the immediate recall. Thus, immediate review with the recall of information helps consolidate memory.^[13]

COGNITIVE LOAD AND MEMORY CAPACITY

Working memory for active information processing includes both short-term and long-term memory components. Short-term memory for the acquisition of new information is limited. It is generally possible to keep only 5–9 separate pieces of new information from sensory input in short-term working memory at any one time. Between 2 and 4 of these pieces can be processed simultaneously, and only for a few seconds. Almost all of this new information is lost after 20 s unless it is refreshed through review. Learners may learn and forget the same information multiple times before this new information gets into their working memory. Novice learners are trying to process many new variables, and the possible combinations of those variables are a mathematical factorial or combinatorial, multiplication, and not simple addition. Information available from long-term memory becomes organized by schemas that can be complex but also automated and not only limited to just a few items at a time. Experts are automatically using extensive long-term memory for working memory, while novices are struggling to process new information with short-term memory. Expert schemas are reinforced through multiple usages. In healthcare institutions with many employees, turnover and intermittent or infrequent task completion create more novice learners.^[14]

There are cognitive limits to acquisition of information through reading. Novice students may read at a rate no more than 150 WPM, and for the acquisition of information needed to pass high stakes, examinations may read no faster than 50 WPM. Content experts as instructors of novice students will skim and scan at 400–600 WPM. This explains why experts can become frustrated with novices and why experts designing

information systems may overlook difficulties encountered by novices attempting to acquire new information. Information transfer through an electronic health record (EHR) requires reading, and EHR usage for patient care may be considered a high-stakes task.^[15] Thus, informaticians may consider how quickly EHR users can absorb the information provided in the narrative (word) format.

Cognitive load is a function of intrinsic load and extraneous load. Intrinsic load is defined by the number of new information elements to be processed simultaneously and by element interactivity: how closely the information elements are related to one another. For example, one could more easily process new information about similar laboratory tests, such as electrolytes. However, elements with high levels of complexity, such as criteria for the diagnosis of carcinoma, may require additional cognitive resources. Extraneous load is a function of the learning process. Extraneous load is high for trial and error learning, particularly when a novice learner has to search out the information needed (e.g., computer searching). Extraneous load is high with multitasking because there is a cognitive load to shifting attention from one task to another, requiring reorientation to thinking. When long-term memory schemas for organizing data elements are developed, then a greater intrinsic load can be handled. Intrinsic load can be reduced by breaking down complex learning tasks into a series of simplified tasks. As learners progress, they can begin to handle more information. Intrinsic and extraneous cognitive loads are additive, and even a simple learning problem can be made difficult by poor design of systems providing information.^[14,16]

The visual mode of learning may have advantages for memory storage. Visual long-term memory representations can be detailed. Long-term memory for objects in scenes can contain more information than only the gist of the object. Human memory is capable of storing fairly detailed visual representations of objects over long time periods. In one study observers could successfully remember details about thousands of images after only a single viewing. Whereas in everyday life we may often fail to encode the details of objects or scenes, the study results suggest that under conditions where we attempt to encode such details, we are capable of succeeding.^[17]

STRESS AFFECTING COGNITION

Conditions involving stress can alter memory. The stress hormones epinephrine and cortisol are released during emotional arousal and can modulate synaptic consolidation and memory strength. Emotional arousal leads to activation of the amygdala of the limbic system to modulate memory storage, which may produce more strongly encoded memories. However, there is an inverted U-shaped dose-response relationship between stress hormone levels and memory performance. Very high or low levels of stress during an event may reduce memory for the event. Thus, in states of arousal, memory encoding may be enhanced or impaired depending on the stress level and a person's individual stress response.^[7]

The cognitive process of retrieval of arousing information leads to a reactivation of the amygdala, which can lead to further strengthening of memory, but distortions can occur if any aspect of the retrieval or reconstruction of the memory is erroneous. As the retrieved information is re-encoded, these distortions, whether self-generated or externally suggested, can potentially become part of the memory. High levels of cortisol during retrieval have been shown to impair memory retrieval. Arousal may enhance memory for some aspects of an event and impair memory for other aspects. As an example of high stress, violence and trauma tend to improve memory for the central gist of an event (e.g., witnessing a homicide) but impair memory of the peripheral details of the event (e.g., the clothing of the perpetrator).^[7]

Memory fragmentation and dissociation affect the information acquisition. Memory fragmentation includes abnormalities of sequence, coherence, and content in a recounted narrative. Fragmentation is thought to result from a lack of elaboration of the memory due to high emotion and dissociation during a stressful, traumatic experience. Dissociation is a term used to describe a disruption in the usually integrated functions of consciousness, memory, identity, or perception. Dissociation during a traumatic event prevents elaboration during encoding, which disrupts both memory storage and retrieval. Distress or emotional arousal during memory encoding may affect memory fragmentation. Dissociation during a traumatic event may prevent encoding of threatening, aversive memories and may be a protective mechanism against "bad" memories. However, dissociative encoding with incomplete initial processing of the traumatic experience, either during or following a trauma, may lead to fragmentation of the trauma memory, linked to the development and persistence of posttraumatic stress disorder.^[18] Dissociation in the workplace can affect the ability of the healthcare team to retrieve and use information.

A heavy information load can affect the performance of an individual negatively, whether measured regarding accuracy or speed. When information supply exceeds the information-processing capacity, a person has difficulties in identifying the relevant information, becomes highly selective and ignores a large amount of information, has difficulties in identifying the relationship between details and the overall perspective, needs more time to reach a decision, and does not reach a decision of adequate accuracy.^[19] Information anxiety is a term describing a condition of stress caused by the inability to access, understand, or make use of, necessary information. A coping strategy for information overload is satisficing, taking just enough information to meet a need, rather than being overwhelmed by all the information available, assuming just enough information is good enough.^[20] A study of primary care providers using comprehensive EHRs showed that they are vulnerable to information overload, which might lead them to miss important information.^[21] Information overload can be reduced if efforts are made to assure that it is of high value and is delivered in the most convenient way and format that is visualized, compressed, and aggregated.^[19]

COGNITIVE DISTRACTION, ATTENTION, AND MULTITASKING

Attention span plays a role in the reception of information but is difficult to measure because it is person, place, and task dependent. In the context of neural information processing, a 20 min upper limit to short-term memory processing and transfer would be predicted.^[10] Technology, entertainment, and design talks do not exceed 18 min.^[22] A study of students watching online videos from 4 to 24 min in length showed that attention, as measured by completion in watching the video, could be increased by adding elements of interactivity while watching. However, overall completion rates averaged 76%.^[23]

Working memory capacity for any person is strongly predictive of his or her performance on a wide variety of high-level cognitive measures, such as fluid intelligence, abstract reasoning, mathematics and language abilities, and overall academic performance, but these individual differences are determined primarily by variability in consistently deploying attentional control over what is stored in working memory. Low-capacity individuals have more difficulty ignoring distracting information than do high-capacity individuals, in part because they are slower at disengaging attention from irrelevant information that captures their attention.^[16]

Multitasking is actually multisequencing of tasks performed in short sequences in close approximation. More tasks attempted shorten the sequences. It is difficult to comprehend complex biomedical information in short time frames. A “problem state” is a directly accessible intermediate representation of the current state of a task. If each task requires a problem state to be maintained, even for a few seconds, then separate tasks interfere with each other. Performance levels will decrease if two tasks both require the maintenance of intermediate information in short-term memory. If two tasks attempt to retrieve a fact from memory at the same time, only one task can proceed.^[24]

Information processing for decision-making may use either exploratory or exploitative methods. Exploratory decision-making employs the gathering of information from multiple sources, involves the use of the brain’s frontopolar cortex, and requires careful mental regulation. In contrast, the decision-making process may focus on exploiting a single source of information deemed to be high-yield, involves the use of striatum and ventromedial prefrontal cortex, and employs unconscious habitual mental processing of information. Gathering or exploiting information represent opposing demands, balancing the desire to select what seems, on the basis of accumulated experience, the richest option (exploitative), against the desire to seek a less familiar option that might turn out to be more advantageous (exploratory).^[25]

A study comparing use of media in multitasking showed that heavy media multitaskers, defined as one standard deviation or more above the mean number of media a person simultaneously consumes when consuming media, are more

susceptible to interference from irrelevant environmental stimuli and from irrelevant representations in memory than light media multitaskers (one standard deviation or more below the mean). Heavy media multitaskers performed worse on a test of task-switching ability, likely due to reduced ability to filter out interference from the irrelevant task set. Heavy media multitaskers were distracted by the multiple streams of media they were consuming and more likely to employ exploratory, rather than exploitative, information processing, sacrificing performance on the primary task to let in other sources of information. Low media multitaskers were more likely to employ top-down attentional control and focus their attention on a single task in the face of distractions. Thus, multitasking with many media inputs is a way to find sources of information, but not comprehend them.^[26] The findings of a study of college students suggested that multitasking students will actually need more time to achieve the same level of performance on an academic task.^[27]

Distractions can occur in the form of noise. In one study of the effects background noise and interruption on learning health information, the group of students watching a videotape with no distraction learned significantly more than a group watching the videotape with noise and with interruption, suggesting that distraction during health teaching adversely affects the ability to learn health information.^[28] Background noise interferes with comprehension, and noise in the form of irrelevant (not on task) but meaningful (can be understood and processed) native language speech is most disruptive.^[29]

COGNITIVE BIAS AND FLEXIBILITY

The process of filtering information may be modified by individual bias. Persons of differing political and religious persuasions can view the same data and come to strikingly different conclusions regarding the data.^[30] An integrative patient EHR could include race, gender, and address. Do demographics prompt bias towards certain patients?^[31]

The use of cognitive flexibility, the ability to selectively switch between mental processes to generate appropriate responses, may aid complex learning situations. The learner can recognize common beliefs and misconceptions that apply to related concepts, and challenge those misconceptions by switching to another mental process. This form of flexibility is illustrated by the misconception that any urethritis is gonococcal and therefore a sexually transmitted disease. This misconception can be challenged by switching to the awareness that multiple infectious agents can cause urethritis and noninfectious cause as well. Cognitive flexibility can involve de-emphasizing compartmentalization of knowledge. An illustration is the problem of “linear thinking” to oversimplify complex problems into simple, exclusive, sequential “cause and effect” events. For example, an understanding that Paget disease of bone results in an increase in the serum alkaline phosphatase may lead to linkage of this laboratory test exclusively with that disease, ignoring the more complex relationships of alkaline

phosphatase to multiple bone diseases, or to other sources, such as biliary tract, gastrointestinal tract, or placenta.^[32,33]

COMMUNICATION BARRIERS

Information transfer, whether written, auditory, or visual, is not precise. As an example, what was said and what is heard are not congruent. Some of what we say will not be heard by others, while some of what others thought we said was never said at all. The amount of congruence depends on multiple factors, including individual differences in providing and receiving information. When health care providers speak to patients, 40%–80% of medical information is forgotten immediately, almost half of the information that is remembered is incorrect, and the greater the amount of information presented, the lower the proportion correctly recalled.^[34] In a study involving college-age students, mean correct recall of medical instructions was 14% when listening only, but 85% with pictographs included as visual aids.^[35]

Jargon and idiom affect communication with information transfer. Every branch of health care with discipline experts has its own unique language elements not immediately understandable to others. The use of medical jargon in communication may negatively affect credibility.^[36] Information content experts must be cognizant of the language used in communication to persons outside of their expertise. Increasing use of multidisciplinary healthcare teams requires clear communication among team members.^[37]

WORKPLACE ENVIRONMENT

Civility is an organizational system value that improves safety in healthcare settings. Civility in the workplace can be defined as behaviors that show respect toward another person, make them feel valued, and contribute to mutual respect, effective communication, and team collaboration. Conversely, workplace incivility can be defined as “low-intensity deviant behavior with ambiguous intent to harm the target, in violation of workplace norms for mutual respect; uncivil behaviors are characteristically rude and discourteous, displaying a lack of regard for others.”^[38] Workplace bullying refers to repeated, unreasonable actions of individuals (or a group) directed towards an employee (or a group of employees), which are intended to intimidate, degrade, humiliate, or undermine; or which create a risk to the health or safety of the employee(s).^[39]

Incivility is marked by rudeness that is contagious and causes persons to be rude when interacting with others. When teams experience rudeness from within or outside the team, there are catastrophic effects on team dynamics and performance, consuming resources that could have been focused on task achievement, problem-solving, and patient care. Persons who are targets of rudeness are less likely to be helpful after experiencing rudeness. Rudeness disrupts conscious cognition by automatically activating the limbic system of the brain, a “fight or flight” response over which persons have no control. There is an informational challenge to process what is being

received and how to respond. Attention is diverted from the task at hand. Even viewing an incident of incivility toward another person negatively affects the viewer. Incivility increases stress, impacting cognitive information processing. In response, health care team members can take care of themselves, recognize what is happening, and seek to surround themselves with supportive persons. They can reduce their exposure to such stresses of incivility and steer clear if possible. They can engage in mindfulness practices and refocus.^[40] One study showed that promoting civility and respect in the workplace may help prevent co-worker incivility, work-related exhaustion, and enhance organizational efficiency.^[41]

COGNITIVE INFORMATICS

Cognitive informatics (CI) combines cognitive, behavioral, and information sciences to inform design of health information technology through analysis of the cognitive and collaborative requirements of work being done by end users. An example of CI processes involved the conversion of information manually written on whiteboards to an electronic information system in an emergency department. Constraints of human limitations informed the refinement of graphical displays providing information to the healthcare team about phases of care including patients waiting, timing of tests, and patient details. End users were satisfied and gave high ratings for the use of the displays.^[42]

Mobile devices in healthcare provide a means to extend the human capacity to recall and process large numbers of variables in support of clinical practice. In one study, user interface design informed a well-designed small screen interface supporting nurses’ response to patient conditions in real time. This user interface design allowed quick learning so that there was no difference in usage between experienced and novice users. There was higher satisfaction with the use of visual symbols.^[43]

EHR’s represents a challenge to the development of interface design for enhancement of patient safety and quality of care. Issues include the amount, size, and complexity of EHR data producing high cognitive load. The American Medical Informatics Association has promulgated recommendations for improving EHR usability. Among those recommendations is the need for a minimum set of design patterns shared among vendors to standardize user interaction in critical patient-safety sensitive functions, just like instrumentation displays for automobiles.^[44] A review of 50 studies involving EHR problems with usability in interface design included impact of and solutions to constraints such as cognitive load, task completion through readability, and effective usage of language.^[45] Another study described a user-centered design process in which foundational design concepts were formulated for an EHR module intended to help clinicians to efficiently complete a summary review of a patient record before an ambulatory visit. Cognitively-based studies were performed with conceptual and visual-spatial aspects of interface design,

including use of card-sort that is also employed in psychologic testing as a measure of attention to task, and the results used to develop a cognitive framework that subsequently guided design of a prototype EHR.^[46]

Visual analytics is the science of analytical reasoning facilitated by advanced interactive visual interfaces to aid reasoning over, and interpretation of, complex data. Visual analytics methods can be used to avoid information overload when people try to analyze a number of variables that surpass the limits of human cognition. The multi-modal and heterogeneous properties of EHR data together with the frequency of redundant, irrelevant, and subjective measures pose significant challenges to users trying to synthesize the information and obtain actionable insights.^[47] An example solution was the development of visualization dashboards providing a user interface to better understand the numerous patient safety event reports, reduce the burden of analyzing the data, encouraging greater data exploration, and improving the discovery of meaningful trends in the data.^[48]

Deep learning carries the potential to address problems of cognitive load and constraints of human information processing. Deep learning describes a class of machine learning algorithms that are capable of combining many raw inputs into layers of intermediate features. Medicine is data-rich, but the data are complex. One strategy for the application of deep learning to imaging informatics is repurposing features extracted from natural images for training, then applying the model to real-world problems. A study of machine deep-learning performance in detection of malignant melanoma showed results as good as or even better than the diagnostic performance of board-certified dermatologist experts. In a concurrent large-scale analysis of EHR data from 700,000 patients, deep learning applied to the number and co-occurrence of clinical events to learn a representation of patients was able to predict disease trajectories within 1 year with over 90% accuracy.^[49]

CONCLUSIONS

People are the ultimate users of biomedical information. Informaticians can recognize the limitations of human cognition and draw upon cognitive science to inform the design and evaluation of technical solutions for information management and interface with the healthcare team. Healthcare workplaces include organizational systems affecting stress levels that impact the use of information by persons working in those systems. Key points:

1. The human brain has a finite capacity for processing new information because neuronal synapse formation with protein synthesis is a rate-limited process
2. The short-term working memory may be limited to no more than 4 separate informational items processed simultaneously. Cognitive load can be reduced by breaking down complex tasks into a series of simplified tasks
3. Long-term memory supplies immediate access to multiple informational items simultaneously

4. Visual long-term memories can be extensive and detailed, so imaging is an effective means for providing information
5. Attention may be task dependent and highly variable among persons. Effective attention span with learning may not exceed 20 min
6. Attention requires attentional control over distracting information. Noise is most distracting when it more closely resembles recognizable human speech
7. Multitasking is multisequencing, and more tasks must be performed in shorter sequences, or tasks compete for working memory, reducing the effectiveness of working memory applied to each task
8. Communication with information transfer is <100% congruent from presentation to reception. Visual aids promote retention of information
9. Cognitive bias affects how information is perceived and applied
10. Stress with emotional arousal can adversely impact memory storage and function when too high
11. The workplace environment can impact cognitive processes, and incivility reduces functional capacity.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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