Framework for Managing Cognitive Load in a Data-Rich Robotic Operating Room

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***Abstract*—Complete autonomy of robots and information technology in the operating room may one day be possible, such that decision support systems give way to decision surrogate systems. A binary of 'control' and 'slave' defines the current relationship between human surgical teams and medical robotics. Yet recognition of our own limitations motivates the development of these technological platforms. Endowed with a modicum of sensory faculties, humans bootstrap their sensitivity to data by enlisting the services of machines. However, in spite of our drive for information in surgery, we often struggle to design work-systems that simultaneously increase situation awareness and limit exposure to extraneous data. Cognitive overload continues to be problematic in spite of attempts to refine and simplify surgical intervention. It is therefore incumbent upon designers to stratify information pathways that alleviate the cognitive burdens stunting pragmatic decision-making in the operating room. We have proposed a framework for this endeavor.**

Keywords—robotic surgery, patient safety, sociotechnical system, industrial engineering, cognitive overload, design, optimization

Glossary of Key Terms

$t = time$

$k = signal\ source$

$x = sense\ type$

$i = surgical\ task\ (technical\ or\ non-technical)$

$j = sociotechnical\ agent\ (man\ or\ machine)$

$a_{k,x,i,t} = amount\ of\ attention\ invested\ to\ signal$

$l_{j,t} = naturally\ discarded\ cognitive\ load$

$r_{k,x,j,t} = rate\ of\ return\ (signal\ to\ cognitive\ load)$

$CL_{j,t} = individual\ cognitive\ load$

$\mathcal{E}\left[U\left(CL_{i,j,t}\right)\right] = expected\ utility\ of\ information\ load$

$K_{j,t} = \{k_1, \dots, k_N\} = signals\ currently\ observable$

$\underline{K}_{j,t} = \left\{\underline{k}_1, \dots, \underline{k}_{\notin}\right\} = signals\ currently\ not\ observed$

$\overline{K}_{j,t} = \left\{k_1, \dots, k_{N-n}, \underline{k}_{1'}, \dots, \underline{k}_{\notin'}\right\}\ mixture\ of\ signal\ types$

I. Introduction

Mitigating and averting cognitive overload is a systems design problem. Unlike when a consumer firmly accepts a product's pros and cons after purchase, surgeons should not have to settle for the ostensible limitations of the cognitive sociotechnical system in the operating room (OR). The system is a product in its own right, with features that are complex and dynamic as is most healthcare delivery [1]. For our purposes the sociotechnical system is comprised of any agent that can share information in the OR—simply put, man and machine.

One utility of a machine is determined by what data it can detect and how well it communicates that data with other entities when they need it the most. From a reductionist perspective, each human is a set of sensory systems with cognitive capacity—a machine of sorts. Electronic devices, robots and other technologies can have sensitivities to data imperceptible to humans, but without sufficient programming the richness of the data economy can overwhelm the humans for which it is intended, or potentially even be squandered by them. While technological barriers currently prohibit perfect synergy between humans and robots, another rate limiting step exists—work. Surgical staff have multiple responsibilities that they must juggle during the course of an operation. These duties are inconsistent across professional boundaries, are not ubiquitous over different timeframes, nor does each task share the same priority [2].

If one clinician is enduring cognitive overload we must consider prioritizing the sources and means of delivering information [3-5], determining the triviality of certain data in the moment, transmitting the right data to avoid additional overload, reconfiguring data so that all mission-critical information can be *chunked* [5-6].

Eliminating cognitive overload in the operating room means marshaling information flow. In order to accomplish this undertaking we must have a good estimation of what the current intraoperative phase is, which data is most clinically important and who is focused on that data. Information theory lends itself to assessing the data volume and uncertainty [7], however we must synthesize this backbone with concepts from psychology and design to repurpose the data for easier detection, articulation and processing.

II. Cognitive Load Theory and Surgery

A human's ability to establish and sustain an appropriate level of situation awareness in an environment depends upon the individual's working memory capacity [8]. This capacity is limited by intrinsic cognitive load and diminishes with larger exposure to external stimuli [4]. Consequently attentiveness to new data, synthesis of old and current information and

articulation of relevant concepts in a timely manner are compromised. Inability to communicate new ideas, request for confirmation or deliver an appropriate response in the OR can cause discrepancies in the collective understanding of surgical stage and protocol [9]. Such divergence can have a malignant effect on intra/inter-team coordination.

Studying working memory capacity and cognitive loads has been attempted in many psychological experiments [10]. Computer simulations have been developed to estimate related metrics in response to different didactic tools and changing environments [11]. Even measures for comparing the similarities between dynamic mental models have been considered [12]. A formal scale, the NASA-TLX index has been used to disavow the notion of "sterile-cockpit" in cardiac surgery because of the variances in cognitive load experienced by different members of the clinical team over intraoperative phases [13].

The input gateways to the human brain are the senses and each individual has finite thresholds for sensory load [14]. As each stimulus signals the brain, the working memory capacity is apt to decrease, though not always [4]. The information that humans absorb in the operating room comes primarily from four senses—sight, audition, tactition and proprioception. Gatekeeping data is profoundly important, or else information overload will ensue.

The emergence of technologies that collect data from eye gaze, electric signals in the brain, heart rate, pressure, sweat etc. during activity elucidate upon the duress endured, mechanisms activated and allow for more complete models of cognition [15]. Leveraging these innovations in the operating room can have an acute effect on gauging how prone a clinician might be to committing an error. Furthermore if latent cognitive loads inhibit rational decision making and group engagement, then accurate and quick detection of reduced working memory capacity could allow an intelligent system to preempt dialogues before information is left unconsidered.

III. System Design

Unlike with conventional design theory, when the sensory mechanisms of humans do not satisfy all of the operational needs there is little opportunity to augment their range of sensitivity or add another sensory organ in real-time. Humans are the way they are: a completed package, fallible and require help.

An ideal design demands that at a given time each functional need is performed by a single component, which prevents undue coupling [16]. Surgical staff are often forced to meet multiple needs simultaneously and their sensory processing systems are being innervated by more than one stimulus at a given time. Resource competition theory of cognition intimates that in spite of sufficient resources of neurons to handle various sensory inputs at a given time, the human brain is wired such that perception of external data creates a hegemonic conflict for the same neural networks [17]. Ability to use a sense for perceiving task performance appears to be coupled with both the concomitant tasks and other senses being activated. Therefore a smart distribution and partitioning of the sociotechnical product is needed for improving work efficiency from a human perspective [18].

IV. Template Optimization Problem

Dynamic portfolio analysis

The first step in our solution method is to optimally distribute intraoperative information to clinicians given their current sensory loads and task-related needs. This means that their cognitive load must be held below a certain threshold and the utility of the information provided to them maximized. Such a process is akin to managing an investment portfolio across different time frames [19]. In this step, the market is constrained to one person and information resources are shuffled to various senses. This is iterated for each person and we first create a map of best information dispersion for each individual to best accomplish the goals set out for them.

Some key assumptions we have made are:

- the activity of all four senses in question can be measured in real-time
- a probabalisitc model can be constructed to demonstrate the likelihood of sensory occupation with a task
- cognitive load, sensory and working memory can be quantified and approximate overload thresholds defined
- the relationship between specific task perfomance and outcomes measures is known

Each team member has a task-specific cognitive load measured at every time step, Eqn (1). Cognitive loads for each successive time step are determined by the previous cognitive load, an estimate reduction in load caused by limitations in human working memory, the sensory attention dedicated to a given signal and rates of cognitive load return for each sensory commitment. Rates of return, $a_{k,x,i,t}$, act as discriminating multiplicative factors because investment in one sense likely influences how much mental stores can be devoted to a different sense or signal.

$$CL_{i,j,t+1} = (CL_{i,j,t-1} - l_{i,j,t}) + \sum_{x=1}^{4} \sum_{\substack{k'=2 \\ k' \neq k}}^{N} \sum_{k=1}^{N-1} (r_{k',x,j,t} - r_{k,x,j,t})\, a_{k,x,i,t} \tag{1}$$

We have written step one of our method as a discounted dynamic programming problem with two objective functions [19]. The first, $\mathbb{O}_1$, imposes a limit on the cognitive load customized to each human agent at a given time. $\mathbb{O}_2$ dictates that the utility of the limited cognitive load must be maximized depending on the goal (or goals) of the human operator.

$$\mathbb{O}_1 \rightarrow CL_{j,t} \leq L_{j,t} \tag{2a}$$

$$\mathbb{O}_2 \rightarrow max\{\mathcal{E}[U(CL_{j,t})]\} \tag{2b}$$

A weighted multivariable utility optimization [20] will most likely be required because staff typically are concerned with patient safety, stability and resource utilization among a litany of other factors.

Asset selling

Ultimately however we are not striving to optimize the performance of individual agents autonomously, but to create a global system optimum for the OR so that all of the desired outcomes are achieved. The second step of our conceptual method is to expand the sensory marketplace to include all individuals, and eventually technologies. Similar to the financial analogy described above, information can be used as a currency whose value depends on how much utility it confers to the user [19]. If a global optimum can be achieved through exchange of information (or in this situation engineering the likelihood of an agent receiving that information) then these data assets should be traded fluidly.

Instead of moderating which information types are appropriate for just one person to complete a set of tasks with given priority, the second step allows for data carrying a semantic and clinically-relevant property to be distributed among agents in the OR sociotechnical system. For example, let us assume that there are two clinicians (j=1,2) in the operating room each able to observe one information bearing signal apiece, k_1 and k_2. Due to physical partitions in the OR both clinicians are obstructed from observing the other signal. According to this definition, $K_{1,t}=\{k_1\}=\underline{K}_{2,t}$ and $K_{2,t}=\{k_2\}=\underline{K}_{1,t}$. However, should the utility of receiving information conveyed by k_1 be more valuable than k_2 to j=2 at a given instance, then j=2 can "sell off" or discard k_2 so that he can be delivered k_1. This is not to say that we are censoring signals altogether, but rather limiting their exposure to those who might want or need them more. This is analogous to resituating a left-handed person to the left-end of a rectangular dinner table if they are bumping arms with their neighbor or offering a sign-linguist for the hearing impaired.

The decision rule for a next-state oriented scope is elementary.

$$if \quad \max_{\underline{K}_{j,t}}\{\mathcal{E}[U(CL_{i,j,t+1})]\} \geq \max_{K_{j,t}}\{\mathcal{E}[U(CL_{i,j,t+1})]\} \qquad (3)$$
$$then \text{ "sell" } \{k_{N-n+1}, \dots, k_N\}, \text{"purchase" } \{\underline{k}_{1'}, \dots, \underline{k}_{\notin'}\}\ after\ t$$
$$otherwise\ keep\ K_{j,t} = \{k_1, \dots, k_N\}\ for\ t+1$$

However, what if we want to maintain a certain level of observable signal stability such that immediate information needs are trumped by routing policies that will likely yield more longitudinal efficiency and success? In such a case we would expand the horizon limits of our time frame [19].

V. Applications in the Robotic Operating Room

Present Day

Although Wadhera and associates measured disparities in cognitive loads between teams during intraoperative phases, there is no implication that manufacturing differentials in cognitive load alone enables sufficient situation awareness and application of other non-technical skills by less affected teams [13]. This level of assessment must be done for each clinician. Nonetheless, teams' interdependent workflows during surgery mandate essential communications of data which inform the decision to safely proceed with the next task [9].

Inclusion of a control-slave medical robot, like the da Vinci (Intuitiv Surgical, Inc, Mountain View, CA) into the milieu of the OR has the potential to exacerbate information communication dilemmas because of the physical disconnect between surgeon and other clinicians, limiting the sensory parity [2,21]. While some ORs are retrofitted with microphone systems that amplify voices to be fed through room or robot-control speakers, the ability to detect change and make inferences based upon directed or incidental observations is severely compromised. Thus, improving the mechanism for hearing communications does not rectify the issue of knowing when to elicit the correct information, but instead serves as a specious solution. Attentional blindness to these external events may in fact diminish a surgeon's external sensory or cognitive load, but the positional change from the table to the robot controller forces a surgeon to exert more effort in constructing and updating a mental model of team dynamics [3]. Working with robot in the OR introduces this complication as an unacceptable backslider.

Near Future

Having the ability to quantify cognitive load can be instrumental in eliminating denial as a deterrent from seeking help. Psychologically, some surgeons might be conditioned to believing that asking for assistance is tantamount to conceding their own shortcomings [22]. After hours of operation and the need to manage (or be observant of) many facets of care coordination, both physical and mental fatigue become salient obstacles to prudent decision-making. In a high-consequence environment like the OR, the perceived need to preserve ego and reputation should be relegated in priority compared with the overarching goal of providing therapeutic intervention for patients. If a personal cognitive load threshold is met, then the system could cue the OR suite manager of a need for relief.

From a robotics perspective, this same recognition could signal an array of "on-call" systems to gradually assume many of the menial or peripheral responsibilities (physical or supervisory) so that the surgeon can remain fully concentrated on the technical craft. In such a fashion, humans are not relinquishing control of the operating room to automation *per se*, but instead allow their confidence in cognitive surveillance to maintain continuity. What was once known as computer supported collaborative work could be afforded a new moniker—cognition attentive robotic assistance (CARA). Automobiles now have the ability to prompt steering correction for the drowsy driver and mobile phones adjust their setting when attention is diverted away from the screens. Because of these advancements, applications to the manipulation of robotic instruments appear tractable. Although some pundits will undoubtedly remark that human control in the surgical domain must remain sacrosanct, hopefully this serves as an acceptable compromise.

Distant Future

Looking more towards the distant horizon we can conceive a future where the cognitive loads experienced by surgical staff do not just prompt the OR information technology network to algorithmically rearticulate information or activate robotic "auto-pilot" features, but to dictate the physical and functional identities of machines themselves.

As morphogenic robots mature conceptually [23] and become actively integrated into the conversation of appropriate functionality in the OR, we envision that information “shunting” will also play a key role in determining what structural adaptations have a high-degree of fitness in an evolving environment.

VI. Conclusion

In assessing the novelty of this method, we do recognize that others have embraced a similar approach [24-25]. However these formulations are within a different context, use different inputs and have dissimilar time constraints. It should be noted that our method remains a kernel of an idea rather than an empirically validated approach. Nevertheless we feel strongly that measurement of cognitive and sensory loads for the reconstruction and rearticulating of information signals in the OR has significant potential to push the envelope of surgical patient safety innovation.

The objective is thus to alleviate cognitive overload by entrusting a larger cognitive network to remediate individual oversights and misinterpretations of information. However competent a surgical worker may be, he or she can only metabolize a limited amount of information while performing clinical task-work. Crafting a system that ensures clinicians’ working memory can be strictly geared towards recalling medical training, past scenarios, previous patient status and developing case strategies instead of being inundated with superfluous information should be the underlying motivation. By our hypothesis, this will reduce the amount of preventable errors [26].

Constant fluctuation of task performance is not appropriate for people in a live OR. Some consistency must remain. Therefore the time intervals for measuring sensory loads and estimating informational utility require litigious selection. Custom, training deficits, dependence on protocol and human fallibility would most likely prohibit safe execution of tasks in a constantly changing environment. However, each moment of time provides a glimpse into how the sociotechnical system is structured and thus we can provide snapshots of potential improvements. Humans and technology should work collaboratively where the shortcomings of one can be compensated for by the other’s abilities. Should the extant agents not complement each other perfectly, then that is evidence for an innovative need.

REFERENCES

[1] Plsek, Paul. "Redesigning health care with insights from the science of complex adaptive systems." *Crossing the quality chasm: A new health system for the 21st century* (2001): 309-322.

[2] Carroll, John M., et al. "Notification and awareness: synchronizing task-oriented collaborative activity." *International Journal of Human-Computer Studies* 58.5 (2003): 605-632.

[3] Langley, Pat, John E. Laird, and Seth Rogers. "Cognitive architectures: Research issues and challenges." *Cognitive Systems Research* 10.2 (2009): 141-160.

[4] Van Merrienboer, Jeroen JG, and John Sweller. "Cognitive load theory and complex learning: Recent developments and future directions." *Educational psychology review* 17.2 (2005): 147-177.

[5] Cowan, Nelson, et al. "On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes." *Cognitive psychology* 51.1 (2005): 42-100.

[6] Miller, George A. "The magical number seven, plus or minus two: some limits on our capacity for processing information." *Psychological review* 63.2 (1956): 81.

[7] Shannon, C.E., Weaver, W., *The Mathematical Theory of Communication* (1949) University of Ilinois Press, Urbana

[8] Endsley, Mica R. "Toward a theory of situation awareness in dynamic systems." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 37.1 (1995): 32-64.

[9] Yule, S., et al. "Development of a rating system for surgeons' non-technical skills." *Medical education* 40.11 (2006): 1098-1104.

[10] DeLeeuw, Krista E., and Richard E. Mayer. "A comparison of three measures of cognitive load: Evidence for separable measures of intrinsic, extraneous, and germane load." *Journal of Educational Psychology* 100.1 (2008): 223.

[11] Sawicka, Agata. "Dynamics of cognitive load theory: A model-based approach."*Computers in human behavior* 24.3 (2008): 1041-1066.

[12] Schaffernicht, Martin, and Stefan N. Groesser. "A comprehensive method for comparing mental models of dynamic systems." *European Journal of Operational Research* 210.1 (2011): 57-67.

[13] Wadhera, Rishi K., et al. "Is the “sterile cockpit” concept applicable to cardiovascular surgery critical intervals or critical events? The impact of protocol-driven communication during cardiopulmonary bypass." *The Journal of Thoracic and Cardiovascular Surgery* 139.2 (2010): 312-319.

[14] Lavie, Nilli, and Jan W. De Fockert. "Contrasting effects of sensory limits and capacity limits in visual selective attention." *Perception & Psychophysics* 65.2 (2003): 202-212.

[15] Vogel-Walcutt, Jennifer, and Julian Abich. "Using neurophysiological data to inform feedback timing: a pilot study." *Foundations of Augmented Cognition. Directing the Future of Adaptive Systems*. Springer Berlin Heidelberg, 2011. 265-274.

[16] Suh, Nam P. "Axiomatic design theory for systems." *Research in engineering design* 10.4 (1998): 189-209.

[17] Scalf, Paige E., et al. "Competition explains limited attention and perceptual resources: implications for perceptual load and dilution theories." *Frontiers in psychology* 4 (2013).

[18] Braha, Dan. "Partitioning tasks to product development teams." *Proceedings of ICAD*. 2002.

[19] Bertsekas, Dimitri P., and Dimitri P. Bertsekas. *Dynamic programming and optimal control*. Vol. 1. No. 2. Belmont: Athena Scientific, 1995.

[20] Tan, Weiping, et al. "Multiobjective Optimization in Multifunction Multicapability System Development Planning." 1-16.

[21] Goodwin, Dawn. "Upsetting the Order of Teamwork: IsThe Same Way Every Time'a Good Aspiration?." *Sociology* 41.2 (2007): 259-275.

[22] Wetzel, Cordula M., et al. "The effects of stress on surgical performance." *The American journal of surgery* 191.1 (2006): 5-10.

[23] Jin, Yaochu, and Yan Meng. "Morphogenetic robotics: An emerging new field in developmental robotics." *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 41.2 (2011): 145-160.

[24] Yassine, Ali A., Ramavarapu S. Sreenivas, and Jian Zhu. "Managing the exchange of information in product development." *European Journal of Operational Research* 184.1 (2008): 311-326.

[25] Hou, Ming, et al. "Optimizing Operator–Agent Interaction in Intelligent Adaptive Interface Design: A Conceptual Framework." *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 41.2 (2011): 161-178.

[26] Zegers, Marieke, et al. "The incidence, root-causes, and outcomes of adverse events in surgical units: implication for potential prevention strategies." *Patient Saf Surg* 5 (2011): 13.