The Limitations of Limitations

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One of the principles of human-centered computing, the Aretha Franklin principle,[1] states,

> Do not devalue the human in order to justify the machine. Do not criticize the machine in order to rationalize the human. Advocate the human–machine system in order to amplify both.

The implication we pursue in this article has to do with the notion of human limitations.

In the introduction to his text on engineering psychology, Christopher Wickens wrote, "One major purpose of this book is to examine human capabilities and limitations in the specific area of information processing. The second purpose is to demonstrate how knowledge of these limitations can be applied in the design of complex systems with which humans interact."[2] The first sentence in this quotation clearly recognizes that humans have capabilities. However, the second sentence seems to imply that it is the limitations that are most relevant in the design of complex systems.

In a similar vein, Barry Kantowitz and Robert Sorkin wrote, "Indeed, many human factors analysts believe that *minimizing human error is the primary goal of any human factors design*. If people never made errors, there would be little need for a science of human factors" (italics added).[3] Such statements, and there are scads of them in the literature, portray the human as the weaker link in any complex system. And the design focus tends to be on protecting the system from the limitations and errors that are associated with that weak link.

In this essay, we argue that human factors and applied cognitive psychologists have not just been selective in regarding certain human characteristics as limitations, but also have selected the wrong things and for the wrong reasons.

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Selecting the wrong things: The myths of human limitations

Throughout the literatures of cognitive science, computer science, and human factors, you can find all sorts of references to the idea that people have memory, attention, and reasoning limitations. The mind-set in human factors engineering has been cast along the dimensions that Paul Fitts and his colleagues established with their MABA-HABA (Machines Are Better At versus Humans Are Better At) List.[1] The capabilities and limitations of humans and machines are measured against each other, but there is also a tacit value judgment—that machines' capabilities compensate for human limitations. For example, Donald Norman attributes the focus on human limitations to a "machine-centered bias," in which the human is evaluated relative to machines' positive attributes and found to be wanting.[4]

In accordance with the entrenched tradition of Fitts' List, new PhDs in psychology are required be able to parrot the old saw, "Human working memory is limited." The notion of limited capacity in working memory goes back to the earliest studies of human memory, by Sir William Hamilton (memory for random scatterings of marbles) and Herrmann Ebbinghaus (memory for lists of syllables).[5] These pioneers in the study of memory discussed what they called the "span of immediate apprehension." With the rise of cognitive psychology, this came to be dubbed the "7 ± 2 chunks" limitation to short-term memory[6] or working memory.[7] The basic notion became entrenched with the advent of the modern computer and the affiliated metaphors for mind, in the classic works of such individuals as Herbert Simon.[8–10]

We know that with sufficient practice at immediate

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recall for particular kinds of materials (for example, strings of numbers, restaurant orders, and so on), we can push this so-called "limitation" to accommodate surprisingly large amounts of material.[11] Studies of expertise have shown clearly that the amount of information people can integrate into chunks is rather flexible and domain-dependent. (We are tempted to say it is limitless, but this would be hyperbole.) So although there might be constraints on the number of chunks people can deal with effectively, and although 7 ± 2 might be a good ballpark estimate of that constraint, 7 ± 2 is hardly a limitation in the sense of a practical bound on the span of immediate apprehension. Rather, it might reflect a constraint on how that material must be organized.

As for the treatment of long-term memory in the literature, we find praise for human

- Memory in general,[12] with total memory capacity estimated to be approximately 10^8 to 10^9 "memories"[13]
- Memory for vocabulary[14]
- Ability to recognize thousands of pictures[15]
- Ability to become an expert possessing extensive, organized domain knowledge[12,16]

On the other hand, some claim that computers have much more extensive long-term memories than do people.[17] This might be true if by "memory" we mean the storage of bits of data. However, if we think about memory as the ability to coherently organize information into meaningful knowledge about the world, then human memory seems to far outstrip the capabilities, let alone the capacity, of current computers. The notions of "storage," "data," "information," "knowledge," and "meaningful" and the nature of the relations among these constructs are, to put it mildly, problematic in and of themselves. They are especially problematic when considered as limitations.

The bottom line is that we can regard any human characteristic as a limitation if we choose to. For any task that humans conduct, performance will have a ceiling at any given time, one that can with practice be pushed toward some asymptote that might represent a specieswide characteristic in the way information and meaning can be assimilated, or in the cognitive resources that are available at any given time.[18]

The selectivity in what is regarded as a limitation shows in the fact that humans have many characteristics that other entities have more of, but we do not choose to see these as limitations. For instance, people have only two eyes, whereas some creatures have more than two. Human vision is constrained to a portion of the electromagnetic spectrum; other creatures can perceive in the infrared and the ultraviolet. Most people have five digits on each major appendage, but some species have seven. Do these characteristics represent human limitations?

Two eyes, five fingers, or 7 ± 2 chunks might be "limitations" to the extent that they constrain how we look at the world, manipulate an object, or organize information. But they are not limitations in the sense of setting hard constraints on the span of seeing, doing, or remembering. Treating them as such results in a distorted view of how humans can fit into human–machine systems.

> Human factors and applied cognitive psychologists have not just been selective in regarding certain human characteristics as limitations, but also have selected the wrong things and for the wrong reasons.

Selecting the wrong things for the wrong reasons

The heart of the problem is a preference for easily quantifiable answers to the wrong questions, and avoidance of the right questions because they are messy. Many in the human factors community cling to the belief that their primary function is to catalog human limitations. This resistance is due partly to their misconception that what designers and engineers need from psychologists is "numbers"—for example, the value of BHEPs (Basic Human Error Probabilities) to be entered into a THERP (Technique for Human Error Rate Prediction) analysis.[19] And the clearest numbers that human factors and applied cognitive psychologists have to offer typically reflect information-processing limitations (for example, the rate of information processing or the capacity of working memory). Approaches such as the GOMS (Goals, Operators, Methods, and Selection rules) model[19] are predicated on the belief that such numbers (for example, reaction time components) can be "integrated" in a way that will provide clear answers to design questions. Certainly the GOMS model and THERP analysis might be important tools for testing some qualitative intuitions about legacy systems, but to think that they can answer any question about the revolutionary redesign of human–machine systems is naïve. Rarely can an engineer or designer enter numbers into a formula and crank out a design solution.

Practical engineering and design are almost always heuristic processes driven by qualitative insights about a process. For example, control engineers rarely compute differential equations or use variational calculus to determine a design problem's solution. More typically, they begin with a heuristic judgment about the "style" of control logic (for example, lead–lag compensation) that will yield a stable solution based on a qualitative understanding reflecting their experiences with other control problems. They usually try this ballpark solution and iteratively tune it to see whether a satisfactory solution results. If not, they might reassess their heuristic judgment and reinitiate the iterative tuning process using a different style of control logic. So, what they need is help to gain a qualitative understanding of the important dimensions to consider when designing cognitive systems.

The challenge of the "chunk"

A second way in which a belief in "numbers" is naïve is that the numbers are considered to be concrete, practical answers. Let's return to the example of short-term memory. To what question is the number "7 ± 2 chunks" an answer? Is it an answer to questions such as

- How many chess pieces can an expert remember?
- How many aircraft can an air traffic control operator manage?
- How many state variables can a nuclear control room operator consider at one time?

After the human factors practitioner has confidently offered this "fact" (which she first encountered in her introductory psychology course), the engineers or designers ask, "What's a chunk?" The response is typically, "It depends on the domain and the person's experience."

The problem is not this answer, which is correct, but that the human factors practitioner abdicates responsibility for digging deeper to help the designer or engineer discover what might be the basis for "chunking" information in that particular domain. This is typically seen as a problem for the "domain experts," whoever they might be. The job of human factors typically ends with quantifying the limitation; the job of translating this "fact" into an effective representation is then left to others—until the human factors practitioner is again called when the system fails catastrophically. At this point, with the benefit of hindsight, the human factors practitioner can confidently count the "chunks" and blame the engineers for exceeding the limits of 7 ± 2 that the human factors researchers had "clearly" prescribed at the start!

So, the 7 ± 2 limit has little practical significance regarding how much information a person can handle in any particular work context. We don't see how any approach to human or machine expertise can progress without researching the different ways that information can be meaningfully integrated (chunked). Information or a database only becomes knowledge when we understand data as information and organize (chunk?) it in some way. Psychologists have focused on limitations and paid almost no attention to the human capability of integrating information into meaningful organizations. As an example of a more productive approach, Kim Vicente and Joanne Wang take an important first step to look at ways to chunk information as a function of structure within problem domains.[20]

Beyond limitations

The cataloging of limitations is such an important part of the conventional wisdom about human information processing that even approaches called "user-centered" design typically mean making sure that the automation doesn't create demands that exceed users' "limitations." Too often, "respect thy users" means adapt the system to this weak link. This is not respect.

Use-centered design[22] is an alternative to this limitations-based approach. In this view, we consider humans and machines as complementary resources for addressing problems of complex work domains. We measure the capabilities of each in terms of the work domain's demands and opportunities, not against each other's "limitations." Similar perspectives are reflected in the concepts of *situated and distributed cognition*[23,24] and cognitive systems engineering.[25–27] A key feature of all these approaches is that distinctions between human and machine components merge into higher-order invariants and conjoint variables, as the focus shifts to systems-level analysis. At this level, we measure "fitness" of the human–machine system against the demands of a situation or work context. And fitness implies more than the absence of error. As in holistic medicine, a systems perspective begins to move past questions of disease to consider questions of health. For design, this means beginning to think in terms of safety rather than exclusively in terms of the blame game of human error. It means shifting the emphasis—from protecting the system against human limitations to leveraging human capabilities most effectively relative to the functional work objectives.

Cognitive systems engineering and HCC should be about the exploration of work contexts and work domains. They should be part of a collaboration with engineers, operators, computer scientists, and designers.

Cognitive systems engineering and HCC should be about the exploration of work contexts and work domains. They should be part of a collaboration with engineers, operators, computer scientists, and designers in the search for qualitative insights into the dynamics of adaptive cognitive systems. How might we integrate information into meaningful chunks that reflect a work domain's demands? How can training or interface design help human operators achieve this integration? Consider not only experts' current thinking about a problem but also the possibility of even better approaches with the support of appropriate training or visualization and representation tools. As a side effect, discoveries resulting from this search might reflect back on theory in a way that offers insight into basic mechanisms of human performance. Clearly, Jens Rasmussen's constructs of skill-, rule-, and knowledge-based processing comprise one example of this.[25] Other examples include Gary Klein's construct of recognition-primed decision making[28] and Edwin Hutchins' ideas about distributed memory.[23]

In HCC, we rely on basic knowledge about human characteristics and then try to develop computational devices that leverage those characteristics. Negative evaluations, such as seeing human characteristics as limitations, are both misleading and unhelpful. Respect is what it is all about. Otherwise, we continue to fight the legendary battle of John Henry versus the steam hammer to see whether human or machine is the winner! Nobody wins when design problems are cast as a competition.

And most significantly, competition between human and machine typically overlooks an important design dimension. Somebody must take responsibility for describing domain constraints so that we can (at least qualitatively) understand the capabilities of both humans and machines relative to the opportunities and dangers that these constraints represent. Human factors engineers who confine their role to cataloging human limitations end up reducing both their opportunity to participate in the design process and their ability to more deeply understand the fundamental properties of complex cognitive systems. ■

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References

1. R.R. Hoffman et al., "A Rose by Any Other Name … Would Probably Be Given an Acronym," *IEEE Intelligent Systems*, vol. 17, no. 4, July/Aug. 2002, pp. 72–80.

2. C.D. Wickens, *Engineering Psychology and Human Performance*, 2nd ed., Harper Collins, New York, 1992, p. 3.

3. B.H. Kantowitz and R.D. Sorkin, *Human Factors: Understanding People-System Relationships*, John Wiley & Sons, New York, 1983, p. 30.

4. D.A. Norman, *Things That Make Us Smart*, Addison-Wesley, Boston, 1993.

5. D. Gorfein and R.R. Hoffman, eds., *Memory and Learning: The Ebbinghaus Centennial Conf.*, Lawrence Erlbaum Associates, Mahwah, N.J., 1987.

6. G.A. Miller, "The Magical Number Seven plus or minus Two: Some Limits on Our Capacity to Process Information," *Psychological Rev.*, vol. 63, 1956, pp. 81–96.

7. A.D. Baddeley, *The Psychology of Memory*, Basic Books, New York, 1976.

8. H.A. Simon, "How Big Is a Chunk?" *Science*, vol. 183, 1974, pp. 482–488.

9. P.H. Lindsay and D.A. Norman, *Human Information Processing*, 2nd ed., Academic Press, New York, 1977.

10. E.A. Feigenbaum, "What Hath Simon Wrought?" *Complex Information Processing*, D. Klahr and K. Kotovsky, eds., Lawrence Erlbaum, Mahwah, N.J., 1989, pp. 165–182.

11. K.A. Ericsson and J. Smith, "Prospects and Limits on the Empirical Study of Expertise," *Toward a General Theory of Expertise*, J. Smith and K.A. Ericsson, eds., Cambridge Univ. Press, Cambridge, UK, 1991, pp. 1–38.

12. D.A. Norman, *Learning and Memory*, W.H. Freeman, San Francisco, 1982.

13. T.K. Landauer, *The Trouble with Computers*, MIT Press, Cambridge, Mass., 1997.

14. S. Pinker, *The Language Instinct*, Morrow, New York, 1994.

15. R.N. Shepard, "Recognition Memory for Words, Sentences, and Pictures," *J. Verbal Learning and Verbal Behavior*, vol. 6, 1967, pp. 156–163.

16. H.A. Simon and W.G. Chase, "Skill in Chess," *Am. Scientist*, vol. 61, 1973, pp. 394–403.

17. P. Fitts, *Human Engineering for an Effective Air Navigation and Traffic Control System*, Nat'l Academy of Sciences, Washington, D.C., 1951.

18. D. Norman and D.G. Bobrow, "On Data-Limited and Resource-Limited Processing," *Cognitive Psychology*, vol. 7, 1975, pp. 44–64.

19. D.P. Miller and A.D. Swain, "Human Error and Human Reliability," *Handbook of Human Factors*, G. Salvendy, ed., John Wiley & Sons, New York, 1987, pp. 219–250.

20. S.K. Card, T.P. Moran, and A. Newell, *The Psychology of Human-Computer Interaction*, Lawrence Erlbaum Associates, Mahwah, N.J., 1983.

21. K.J. Vicente and J.H. Wang, "An Ecological Theory of Expertise Effects in Memory Recall," *Psychological Rev.*, vol. 105, 1998, pp. 33–57.

22. J.M. Flach and C.O. Dominguez, "Use-Centered Design," *Ergonomics in Design*, July 1995, pp. 19–24.

23. E. Hutchins, *Cognition in the Wild*, MIT Press, Cambridge, Mass., 1995.

24. L. Suchman, *Plans and Situated Actions: The Problem of Human-Machine Communication*, Cambridge Univ. Press, Cambridge, UK, 1987.

25. J. Rasmussen, *Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering*, North Holland, New York, 1986.

26. J. Rasmussen, A.M. Pejtersen, and L.P. Goodstein, *Cognitive Systems Engineering*, John Wiley & Sons, New York, 1994.

27. E. Hollnagel and D.D. Woods, "Cognitive Systems Engineering: New Wine in New Bottles," *Int'l J. Man-Machine Studies*, vol. 18, 1983, pp. 583–600.

28. G. Klein, "Recognition-Primed Decision Making," *Advances in Man-Machine System Research*, vol. 5, W.B. Rouse, ed., JAI Press, Greenwich, Conn., 1989, pp. 47–92.

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Erratum

In the Nov./Dec. 2002 essay by A. Endsley and R. Hoffman entitled "The Sacagawea Principle" (*IEEE Intelligent Systems*, pp. 80–85) is the following quotation:

> [In the] tradition we might dub Technology-Centered Design (TCD), system developers specify the requirements for machines, they then implement or prototype the requirements, and finally they produce devices and software. And then they go away, leaving users to cope with what they have built. Indeed, experience has shown that devices that are designed according to the 'design-then-train' philosophy … force users to adapt to the system. The user is entangled with the system terminology and jargons that are the designer's view of the world.[18]

Reference 18 is listed as follows:

18. C. Ntuen, "A Model of System Science for Human-Centered Design," *Human-Centered Systems: Information, Interactivity and Intelligence*, J. Flanagan et al., eds., tech. report, US Nat'l Science Foundation, Washington, D.C., 1997, p. 312.

That is incorrect. The correct reference is as follows:

18. R.R. Hoffman et al., "A Rose by Any Other Name Would Probably Be Given an Acronym," *IEEE Intelligent Systems*, July/Aug. 2002, pp. 72–80.