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Evaluating models in systems ergonomics with a taxonomy of model attributes

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A R T I C L E I N F O

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A B S T R A C T

A model, as the term is used here, is a way of representing knowledge for the purpose of thinking, communicating to others, or implementing decisions as in system analysis, design or operations. It can be said that to the extent that we can model some aspect of nature we understand it. Models can range from fleeting mental images to highly refined mathematical equations of computer algorithms that precisely predict physical events. In constructing and evaluating models of ergonomic systems it is important that we consider the attributes of our models in relation to our objectives and what we can reasonably aspire to. To that end this paper proposes a taxonomy of models in terms of six independent attributes: *applicability to observables, dimensionality, metricity, robustness, social penetration and conciseness*. Each of these attributes is defined along with the meaning of different levels of each. The attribute taxonomy may be used to evaluate the quality of a model. Examples of system ergonomics models having different combinations of attributes at different levels are provided. Philosophical caveats regarding models in system ergonomics are discussed, as well as the relation to scientific method.

1. What is a model?

What do a verbal treatise on how some aspect of an enterprise works, a miniature replica of an airplane, a mathematical equation characterizing human tracking behavior, and a girl posing before a camera or a painter (with or without clothing) have in common? Each is commonly called a model. There are other expressions that normally we do not call models, such as a myth or a poem. However by the broad definition used here they too are models. I am defining a model as *a representation of the structure or function of some selected aspects of our world to one or more observers for the purposes of communicating some relationships, expressing a conjecture, making a prediction, or specifying a design of a thing or a set of events.*

Obviously the term *model* as defined above is very general. In addition to being a *representation* one might use synonyms such as *specification, rendering, map, or characterization* of the relations between elements or variables of some defined set of objects or elements. Then there are semantic overlaps with terms such as *abstraction, construction, explanation, portrayal, depiction, story, theory, idea, concept, paradigm, pattern.*

Narrowing the consideration of models to those used in science, including system ergonomics, we need to add the term *denotative* to the above definition, and make a distinction between that term and *connotative*. Denotation refers to the explicit literal meaning of the words, symbols or signs used to represent the model. Connotation refers to the implied or suggested meaning, as with metaphor. A photo of or a verbal statement about a red rose with a green stem denotes nothing more than a red rose with a green stem, whereas it connotes affection or celebration, depending on context. In science we restrict "model" to denotative representation, and from here on use the term model to mean a denotative model. Thus scientific models can be constructed using words, graphics (e.g. graphs, diagrams, pictures), mathematical equations, physical things or some combination of these. This includes computer simulations that run equations and output numbers, graphs, dynamic animations, etc.

2. Relation of scientific models to system ergonomics

The term *system ergonomics* is assumed here to refer to the theory and application of human behavioral and biomechanical science for analysis and design of complex technical systems involving both people and machines. The additional word *system* particularly implies that system ergonomics incorporates the methods of systems analysis. This includes determination of

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cause–effect (input–output transfer) functions for both human and machine elements, resulting in component models for these elements. The component models can then be combined to predict behavior of aggregate systems or subsystems.

Systems ergonomics includes human interactions with vehicles, computers, and other processes in industrial, business, medical, military or home settings. Having to cope with a system that includes both human and physical variables makes the modeling process necessarily complex. One reason is that the human psychological and biological disciplines come into play along with those of engineering technology, where traditionally these disciplines have employed different constructs and different terminology. The use of system models demands a unified discipline and a commonality in the language of analysis and design.

Both natural and behavioral/social science are increasingly driven by models. In physics, for example, our understanding of the universe is largely based on model extrapolations well beyond what we can observe directly, and huge experimental efforts are made to verify the models (e.g., the hunt for the Higgs boson). However at the current stage of evolution behavioral/social science has not reached that level of sophistication. Nevertheless models serve the function of asserting in a public way what the modeler believes is true about the component cause–effect relationships within the system, which then combine to result in overall system performance. In contrast, modeling in behavioral/social science is farther behind and multidisciplinary tools are needed to assist in model evaluation. To that end a taxonomy of model attributes is proposed here.

3. A taxonomy of model attributes

Table 1 illustrates a proposed general taxonomy of models, with five attributes shown as rows and relative levels as columns. For each attribute are three level descriptors, marked 1, 2 and 3, where level 1 is the least, level 3 is the most of that attribute, and level 2 is in between those limits. If each attribute were considered to have only three discrete.

3.1. Applicability to observables

The first attribute, and the one most coupled to intentionality, is *applicability to observables*. An observable is any evidence amenable to human or artificial sensing or measuring instruments and available to anyone. “Evidence” experienced by one person and not available to others is excluded. Level 1 characterizes models where there is no intention to explicitly describe or predict the real world in terms of observable data, past or present. Evidence in a scientific sense is of no concern here. Such a model might be a metaphorical construct: fiction, poetry, music, abstract art, or dance. In this regard it must be emphasized that metaphorical models need not be of low quality in the sense of value. Life would not be the same without metaphor. Feelings and spirituality are represented in abstract words and music, surely connecting to people, but the meaning or essence of the rendering need not represent explicit data external to the rendering itself. The rendering itself surely consists of data: music has continuous pitch; painting is done in a spectrum of color; and dance is continuous in motion and time. But in this case it is up to the observer to make a connection (or not) between these intrinsic data and any external data. The mapping to the real world is not explicit. Such representations are very different kinds of models from what are published in scientific papers. We call them models at a “low” level, because it is not clear to observers what they are models of. That allows ample room for arbitrary interpretation.

At the other end of the scale a level 3 model seeks to predict with precision some future events based on some well-defined independent variables and a representation of how they interact to produce a result, whether static or dynamic. In between is a description of existing data, a representation of the world as it is. It lacks the transfer functional means to determine a new data output from a new data input. A photograph is an example of this mid-level, or a map. Explications of historical events, where there is no effort to generalize regarding lessons for the future, would also fit this intermediate level.

With regard to *applicability to observables* an ergonomic system designer at first may consider verbal propositions or hypothetical “framework” models that are not bound by any specific data (e.g., hypotheses and conjecture about task analysis, learning, situation awareness, workload, level of automation) at the A1 level. As the design develops, explicit data from completed experiments and experience are likely to be applied (response time, error rates, vision and hearing constraints, etc.) at the A2 level. The goal is to predict success in terms of future data for operator performance measures (A3).

3.2. Dimensionality

The attribute of dimensionality has to do with the number of dimensions of the independent (input) and dependent (output) variable state spaces: how many input and output variables in the model. A model can be single-input–single-output, multi-input–single-output, or multi-input–multi-output. (Single-input–multi-output makes no sense since the outputs would be 100 percent correlated.) The world is complicated, and in general a complex of many outputs (a vector) is a complex function of many inputs (another vector).

It is totally unrealistic to include all inputs and outputs in one gigantic model, even for a narrow slice of reality, so the modeler must always put up with variability that is unaccounted for, presumably by variables not included in the model. One might hope that a single output is mostly related to a single input, but that is seldom the case. If one can find several inputs that relate in

Table 1
A taxonomy of model attributes levels (1,2,3) there would be $3 \times 3 \times 3 \times 3 \times 3 \times 3 = 729$ combinations. However, for each attribute the three levels can also be considered rough descriptors of values along a continuum, yielding a continuous six -dimensional state space.

	Attribute	1 (Least)	2 (Moderate)	3 (Most)
A	Applicability to observables	Not based on observables	Describes past observables	Predicts future observables
B	Dimensionality	Single input, single output	Multi input, single output	Multi input, multi output
C	Metricity	Limited to nominal relationships	Primarily ordinal relationships	Entirely cardinal relationships
D	Robustness	Unique focus on limited objects or events	Moderate focus to a variety of objects or events	Comprehensive of a wide slice of nature
E	Social penetration	Confined to a mental model	Communicated to the relevant community	Accepted and used by the relevant community
F	Conciseness	Wordy, redundant, unclear, ambiguous expression	Minor wordiness, redundancy, or ambiguity	Concise and clear, no redundancy, no ambiguity

combination to a single output that usually accounts for much more variability. Even better (more useful) is to model a relation between a group of inputs and a group of outputs (multiple models in one, so to speak). However a caveat about causality is in order: unfortunately there is no way to firmly establish independence between variables or causality between inputs and outputs (as distinguished from correlation) without encompassing the totality of possible variables and their interactions. Furthermore, when there are closed feedback loops what is considered as input and what as output may be arbitrary.

The *dimensionality* attribute is widely employed in system ergonomic models at both the B1 level (e.g., in tests of significant difference such as Student *t* test, or in factorial experimental designs such as analysis of variance). Multi-input–multi-output relationships tend to be those used in more qualitative (low metricity) modeling such as those employed by clinicians (e.g., a particular pattern of maladies is associated with a given pattern of symptoms).

3.3. Metricity

The attribute of *metricity* (the measurement quality) has to do with the meaning of the variables of the model in the sense of the well-known psychophysical scales of Stevens (1951): nominal, ordinal, interval and ratio scales. At one extreme the relationships are expressed in variables that are only nominal (name) categories. At the other limit of metricity are relationships expressed in variables that have a cardinal property of continuous quantitative values (one can consider equal ratio relations as the very limit with equal intervals close behind). In between are ordinal relationships, expressions that X is greater (e.g., better) or lesser than Y.

The *metricity* attribute is mostly a matter of the modeler's intent. Human behavior can be represented in words (C1), and much ergonomics literature does that and no more. Human performance modeling mostly implies at least ordinality (C2) – that something is bigger, faster, or better by some criterion. Models that predict in cardinal relationships (C3) are most desirable, because cardinal (continuous numerical) relations subsume order relations and offer greater precision.

3.4. Robustness

The attribute of *robustness* refers to the breadth of applicability. The least robust model is one that has only one purpose, a unique application, and is otherwise useless. At the other extreme is a model that has extremely wide applicability, say Newton's law that Force equals Mass times Acceleration. We can assert that in the ultimate limit a model that applies to everything from atomic scale to galactic scale does not exist, though physicists are working hard to discover such a "theory of everything".

The *robustness* attribute is partially a matter of intent, given that any reasonable modeler knows that the applicability of any human performance model is initially quite limited (D1), though he or she might hope that it can gain wider applicability with time and revision to include other variables and wider use. In system ergonomics it is probably true, and not surprising, that qualitative models (see examples below) are the most robust.

Much of the experimental literature in human factors poses the following modeling problem: An experiment having a relatively simple factorial design is run, with enough subjects in each cell that a conclusion can be made that certain factors are significant at some statistical confidence level (namely some things are significantly better than other things in an order relation). This is useful information, but of limited robustness since the result may not generalize beyond the range of variables compared and the particular task configuration employed.

3.5. Social penetration

The attribute of *social penetration* means the degree to which a model is known, understood, accepted, and used by the appropriate community of people. The scale goes from purely mental models that are confined to internal thoughts of some one person (Moray, 1997, 1998) to models that are widely understood, accepted and applied by a large and diverse community of people. In between are models that are described to others or published in the literature, perhaps in competition with other models for the same application, and perhaps used by only a few practitioners.

In the development of any model, there is a *social penetration* evolution that begins with the initiator's mental model (E1) and possibly evolves over time to full acceptance (E3) by the community (of hardware/software designers, system managers and operators, trainers, human behavioral specialists in health, economics, or etc.).

3.6. Conciseness

I add the attribute of conciseness to provide a metric on brevity of presentation, along with adherence to denotation, clarity and reason. Emphasizing the importance of brevity, denotation, clarity and reason is the principle that has come to be called *Ockham's razor*. This idea was originally attributed to philosopher William of Ockham (1288–1347), according to his pronouncement *Numquam ponenda est pluralitas sine necessitate* (plurality must never be posited without necessity). The gist is that one should use the simplest statement that does not compromise explanatory power. Of course too few words will reduce explanatory power. A hundred-page exposition of an argument, theory, premise or relationship would not normally be considered as a model.

4. Examples of where hypothetical system ergonomic models might Lie within the six-dimensional attribute space

Now let us consider some general categories of systems ergonomic models that combine different levels of the attributes. The conciseness attribute is omitted from the comparisons below.

Referring to the lettered rows and numbered columns of Table 1:

[A1,B1,C1,D1,E1] is a mental model (a musing) assigning some hypothetical simple relation between hypothetical entities, e.g., a perfect human operator perform magic.

[A1,B1,C3,D3,E1] is a mental model of a hypothetical numerical algorithm for general statistical analysis.

[A1,B2,C2,D2,E2] is a hypothetical framework with moderate focus communicated to an interested community. The present taxonomy of models might be an example.

[A2,B2,C2,D1,E1] is a mental model (contemplation) by an experimenter to rank order particular experimental data for later analysis.

[A2,B2,C3,D1,E1] is a mental model based numerical relationships between known data that are broadly applicable within some special industrial context. This might be consideration of a way to analyze cardinal data in a given experiment.

[A2,B1,C3,D2,E3] is an accepted quantitative depiction of past or present facts such as a plot of past athletic records.

[A3,B3,C2,D2,E3] is a predictive, ordinal, well accepted model with moderate applicability. This might be an experimentally-based qualitative or best-practices human factors design guideline that is standard within a given industry.

[A3,B2,C3,D3,E3] is typical of widely accepted and applied models in science and engineering such as Newton's laws as they apply to biomechanics.

At the ultimate limit [A3,B3,C3,D3,E3] is a fully predictive, quantitative model that applies to and explains all of nature and is accepted without hesitation. It is a presentation of relationships between well defined variables pertaining to all objects or events, communicated to others in written words, symbols or graphic images that conveys quantitative structure including explicit cardinal relationships and is demonstrably communicated widely and understood and accepted for use. It is based on data that ere empirically observable by anyone, has a demonstrable record of being predictive within a wide set of circumstances and with high statistical confidence, does not conflict with other models of relationships between the same variables, and applies at all magnitude levels of nature from subatomic to intergalactic. This is what physicists aspire to as the "theory of everything" but have not yet reached, and probably never will. The human sciences are even further behind the physicists.

5. Philosophical caveats

5.1. Modeling as science

Scientific modeling is performed in conjunction with the scientific method, which is typically characterized by a sequence of steps, namely:

1. Make informal observations and consider one or more questions on what is observed. An incipient mental model may already form in the observer's head.
2. Gather information and resources (formal observation).
3. Form a predictive or explanatory hypothesis in terms of independent and dependent variables. This is where a conjectural model begins to take shape.
4. Test the hypothesis by performing an experiment and collecting data in a reproducible manner. The experimental design will have a large effect on what model might emerge.
5. Analyze the data, preferably using appropriate statistical methods.
6. Interpret the data and draw conclusions that serve as a starting point for new hypothesis. This is where the model is refined and formalized.
7. Publish or otherwise communicate the results to peers, rendering the model in a form that best summarizes and communicates the determined relationships.
8. Retest and refine the model (frequently done by other scientists).

We all know that in reality research seldom follows these steps in an orderly way. Francis Bacon (1620) asserted that observations must be collected "without prejudice". But as scientists are real people there is no way they can operate free of some prejudice. They start with some bias as to their initial knowledge and interests, status and physical location, and available tools of observation. They are initially prejudiced as to what is of interest, what observations are made, what questions are asked. Philosopher Karl Popper (1934) believed that all science begins with a prejudiced hypothesis. He further asserted that actually a theory can never to proven correct by observation, but can only be proven incorrect by disagreement with observation. Scientific method is about falsifiability. That is the basis of the null hypothesis test in statistics. The American Association for the Advancement of Science asserted in a legal brief to the U.S. Supreme Court (1993) that "Science is not an encyclopedic body of knowledge about the universe. Instead, it represents a *process* for proposing and refining theoretical explanations about the world that are subject to further testing and refinement".

Historian Thomas Kuhn (1970) offered a different perspective on how science works, namely in terms of paradigm shifts. Whether in psychology or cosmology, researchers seem to make small and gradual refinements of accepted models, until new evidence and an accompanying model provokes a radical shift in paradigm, to which scientists then adhere to for a time. When the paradigm is in process of shifting the competition between models and their proponents can be fierce, even personal (who discovered X first, who published first, whose model offers the best explanation). We also must admit that search for truth is not the only thing that motivates us as scientists. We are driven by ambition for recognition from our peers as well as money. A student of this author once observed that what we did in our lab was piddling with a purpose. There was real truth in that.

The first and most important attribute of modeling and of doing science is reproducible observability. This is because it distinguishes what may be called truth based on scientific evidence of events that are openly observable from those that are not (e.g., personal testimony and anecdotal evidence.) Observability also comes into play at the lowest rung on the social penetration attribute: the mental model. These are models for sure, but being private they are not subject to direct observation by other people.

When subjects are asked to explicate their mental models of how they believe something works, as might be done with subject matter experts in doing cognitive task analysis, there is no external physical access to the mental model. What becomes available is a statement necessarily mediated by how the human subject expresses his thinking in words, which of course could be biased by what the human subject thinks the experimenter wants to hear, etc. Experiments in psychophysics, where subjects make verbal or button push responses relative to observable physical references of sound, light, etc., are assumed to conform more rigidly to scientific method in the sense that responses (e.g. yes, no responses regarding sensory thresholds) involve no verbal filtering. But even here we know from the signal detection literature that even here the threshold judgments can be moved around significantly according to payoffs. Thus observability of the (hypothetical true mental model) is compromised.

5.2. Positivist assumption

Science is generally agreed to be based on the assumptions of positivist philosophy, that: (1) true knowledge is based on empirical observations accessible to anyone with necessary capability (2) findings can be codified into testable theories, (3) results are independent of the investigator, (4) results are transcultural, (5) results are cumulative but always aspire to be disproven, and (6) such knowledge can be unified. So-called scientific method of investigation is generally regarded as being positivist.

Philosopher Auguste Comte considered the scientific method as replacing metaphysics (Bourdeau, 2011), and sociologist Emile Durkheim (1982) saw it as a foundation for social research.

Critics of positivism claim that behavioral/social sciences are distinct from natural science with respect to what exists (ontology) what is justified belief (epistemology). For example, some would claim that the students of history would have to throw out most information, and that "social facts" don't exist "out there" but are necessarily mediated by human consciousness. This view was supported by sociologist Max Weber et al. (1991). Even physicist Werner Heisenberg commented in 1969 (Routledge, 1998): "The positivists have a simple solution: the world must be divided into that which we can say clearly and the rest, which we had better

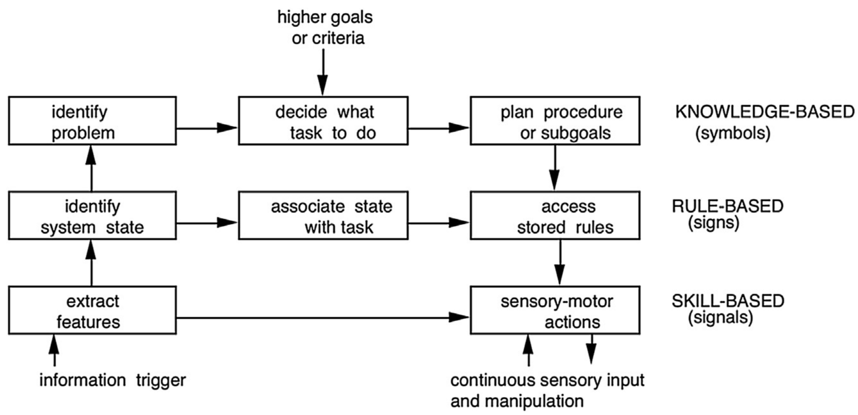

Fig. 1. Rassmussen's skill-rule-knowledge model.

pass over in silence. But can any one conceive of a more pointless philosophy, seeing that what we can say clearly amounts to next to nothing. If we omitted all that is unclear, we would probably be left with completely uninteresting and trivial tautologies".

This paper is not the place to mediate between positivist and anti-positivist philosophies. However I would acknowledge that this paper, and the taxonomy proffered here, assumes a positivist perspective. In any case the taxonomy proposed inherently recognizes that human investigator subjectivity, educational and cultural background and other personal factors to influence the results of any activity in behavioral/social science, including system ergonomics. The extent of any such subjective factors would tend to decrease the degree of each attribute in the taxonomy.

6. Applying the taxonomy to established system ergonomics models

6.1. Skills, rules and knowledge

There are various models that have been extant in system ergonomics for many years that are purely qualitative. Yet they capture relationships that are critical to analysis and design of human-technology systems. One such example is the Rasumussen (1983) skill-rule-knowledge model, typically represented by a diagram such as shown in Fig. 1. I believe that it well enough known to system ergonomists that there is no need to explain it.

This model can and has been applied to many observables, necessarily at an intuitive level because it is qualitative. For the same reason it may be associated with many dimensions, but is explicitly tied to at least the three representing levels (skill, rule and knowledge). It contains no metrics, but one could conjure up ordinal subjective scales around it. Obviously it is very robust, has a high degree of social penetration. It can be stated very concisely.

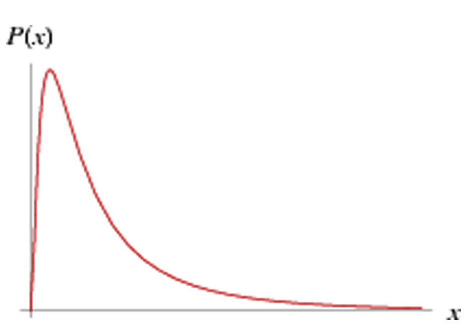

Fig. 2. Log normal probability density model.

6.2. Response time

In contrast to the model described above, now consider a model that incorporates a completely mathematical metric, but for a very focused application. It is based on observable data, is one-dimensional, has modest social penetration at this point, and is very concise It is the so-called log normal probability density function (Fig. 2), which is an excellent model for human response time in a variety of situations (Sheridan, 2013). Some data for trained operators performing a critical response task to a large-break loss of cooling accident in a simulator (Kozinsky et al., 1982)) are shown in Fig. 3. Using special graph paper as shown the figure shows an excellent fit of response times to this model.

6.3. Taxonomies: level of automation and multiple resources

Taxonomies in system ergonomics as well as other disciplines tend to be hypothetical and devoid of explicit data. They tend to include order relationships, and purport moderate generality. Observables abound on the basis of which to apply them. While

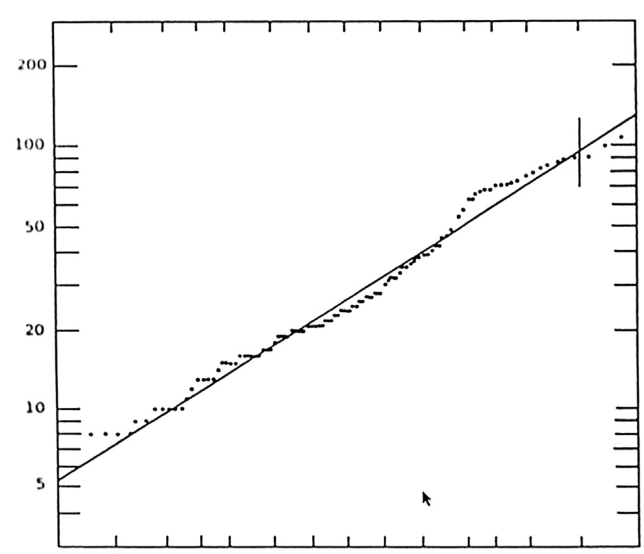

Fig. 3. Data for teams of nuclear plant operators responding to major accident alarm (each point is a different team). By scaling response time logarithmically on the *y* axis and plotting probability that response time is less than indicated value scaled by fractiles of the Gaussian probability density on the *x* axis, a straight line represents a cumulative log normal model.

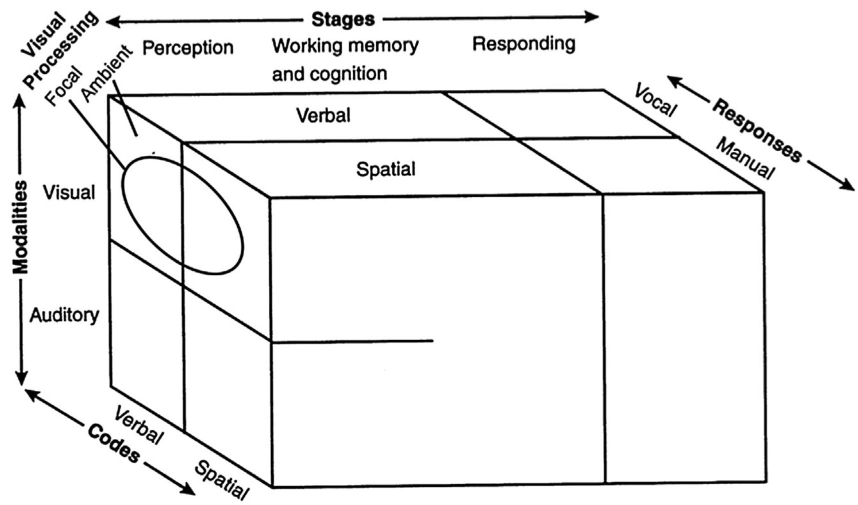

Fig. 4. Wickens' multiple resource model.

communicated to a wider audience within a particular research or application community, they really serve to stimulate thinking (mental modeling) by those concerned to implement more specific models, designs, or policies.

One example is the multiple resource model (Wickens, 1980) in Fig. 4. Another is the scale of levels of automation (Sheridan, 1992) in Table 2. The first is obviously multi-dimensional, the second single dimensional. Such models are useful to the system designer in thinking about design constraints and options. But they do not provide hard constraint information to the designer in the sense of a design algorithm. Using such models to evaluate cognitive constraints such as memory, mental workload, situation awareness, etc. in specific design tasks is territory will not provide hard answers.

6.4. Manual tracking

One of the highest quality (in the sense of this taxonomy) human performance models ever developed is the McRuer and Jex (1967) Crossover Model that specifies the explicit transfer function (as a first order differential equation plus time delay) to characterize the combined human operator and controlled element (G_cG_p) in a target tracking or other feedback control system (Fig. 5). It is elegant because it has a fixed form and comes with a table of (relatively few) parameters with specified dependence on the input bandwidth and controlled element dynamics. In that sense it conforms well to the edict of Occam's Razor (simpler is better). It evolved after many years of government funding to many investigators (including this author) interested in pilots flying high performance fighter aircraft and maintaining control stability. However, even though the Crossover Model set a high standard for human performance models, it is of relatively little interest today because now aircraft are mostly flown on autopilot or fly-by-wire software that provides automated compensation to prevent instability accidents. This is a [A3, B2,C3,D2,E3] model.

6.5. Highway driving

In a different vein, a modeling approach originated by Anderson (1996) called ACT-R (Adaptive Character of Thought) represents procedural knowledge in units called production rules, interacting with declarative knowledge called chunks – all implemented in computer software. This approach is now widely used by other modelers, e.g. for car driving (Salvucci, 2006). The general approach aspires to the [A3,B3,C3,D2,E3] category. One problem with such complex simulator models is that they contain many parameters that are adjusted to provide fit to the data for the given application, so that predictability is limited and adherence to Occam's Razor is a stretch. (They say that with enough parameters one can draw an elephant).

6.6. Anthropometric constraints

Sometimes models have a very direct use in design. One example is the use of computer graphic anthropometric models in the design of workspaces, incorporated into commercial products such as JACK. These computer graphic models allow the user to specify body dimensions (height, arm reach, etc. of male or female at some fractile of the population distribution. A computer manikin can be placed within the proposed graphic simulation of the workspace (aircraft flight deck, automobile seat, etc.) and the

Table 2
Sheridan and Verplank LOA scale (revised).

A scale of levels of automation
1.Computer offers no assistance; human must do it all.
2.Computer suggests many alternative ways to do the task.
3.Computer narrows set of alternatives to just a few.
3.Computer recommends one way to do the task.
4.Computer executes that recommendation when and if human approves.
5.Computer allows human a restricted time to veto before automatic execution.
6.Computer chooses a method, executes, and necessarily informs human.
7.Computer chooses a method, executes, and informs human only if requested.
8.Computer chooses a method, executes, and ignores the human.

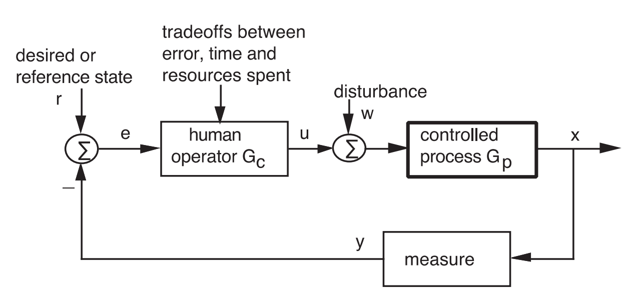

Fig. 5. Classic feedback control model.

manikin can be made to move normally so as to activate certain controls. The exercise will reveal to the workplace designer what will or will not conflict spatially for different size human operators. They are based on large populations of people (the observables) in many dimensions with quantitative metrics, are robust within the class of ergonomic problems they serve, have excellent social penetration, and are quite concise.

7. Conclusions

Modern society makes ever-greater use of explicit models. Dating from early Greek civilization we have had verbal models, but more and more since the Enlightenment we have seen the development of mathematical models. Our ability to run fast-time computer simulations on large databases for human–machine performance in industrial, health, military or transportation contexts has made huge strides in recent years. We have posited many models that can be applied to system ergonomics in the above applications, including system design and operation, anthropometrics, workload evaluation, and training. Especially because human–system interactions are complex and multidisciplinary, it behooves our discipline to develop criteria for evaluating our models. To that end this paper has proposed a six-dimensional taxonomy that might aid in such evaluation.

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