THE CONSTRUCT OF COMFORT: A FRAMEWORK FOR RESEARCH

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ABSTRACT
How we view comfort in scientific terms will determine how we study it. The intuitive model of comfort implicit in research and guidelines until now adapts poorly to failure and to integration across sensory domains. Almost any explicit model will entail recognition of comfort as a construct, not measurable per se, but seen through manifestations. The explicit model can mix physical and nonphysical variables, can accommodate relationships between constructs, and indeed will encourage the search for explanatory constructs, such as health status and vulnerability to discomfort. Structural equation modeling provides a means to analyze interactions between constructs (latent variables) and motivates formalization of the process of discovery.

INDEX TERMS
Comfort, Air Quality, Thermal, Acoustic, Lighting, Modeling, Construct, Latent Variable

THE COMFORTABLE SPACE
Buildings protect people from the outdoors, particularly from extremes of temperature and wind, though also from radiation, rain, and snow, and noise. Buildings protect people from certain air pollutants. Structures will at the same time allow some accumulation of pollutants generated indoors. In the 20th century, with widespread adoption of central heating and air-conditioning in the U.S.A., it became routine for institutional and commercial buildings, e.g., offices, to provide an approximation to general comfort. In principle, this meant that a person could function without involuntary stress from feeling too warm or too cold, from smelling objectionable odors, or from having irritated eyes, nose, or throat. These aspects of comfort typically fall under central control. Although fundamental, the thermal and atmospheric aspects of the environment represent only some of the determinants of comfort. Other physical aspects include the lighting and other visual aspects, the acoustical, and the configurational (spatial layout, size of rooms). Some of these will fall under central and some under local control. A person may, for example, have the chance to choose whether or not to switch on a particular light, to leave a door open for a feeling of spaciousness, and so on.

Given an opportunity to create a simple space, to heat and cool it, to control its air quality, to configure it, to decide on its furnishings, wall and floor coverings, and colors, to light it, to cope with its acoustical features, how would you proceed? Designers and architects routinely plan new hotels. Virtually every hotel seeks to provide comfort, but guests know that design may fail:

1) Heating and air-conditioning units with uncalibrated knobs may leave the guest to guess which setting will make the room neither too warm nor too cool. Some fiddling when the

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guest first arrives may accomplish an acceptable daytime setting, but the uncertainty begins all over again when bedtime comes and the guest seeks a cooler, but not too cool, sleeping environment. When people lose sleep in hotel rooms, they invariably lose time or productivity in their waking day.

2) HVAC units with wide dead bands in their thermostats can allow the room to become too hot before cooling comes on or too cool before heating comes on.

3) HVAC units may make excessive noise, particularly when cooling, and may wake the guest or cause the guest to miss information during a phone call.

4) Bathroom fans may make little difference in the amount of moisture left after a shower, but may add aversive and distracting noise.

5) Plumbing may transmit noise from room to room.

6) Bed lights may cause glare or cast the illumination to the ceiling.

7) Lamps for reading out of bed may be inconveniently placed.

8) Odors may arise from fan coils or may linger from previous guests.

9) Eyes, nose, and throat may become irritated from chemical emissions.

Ironically, even the poorly designed hotel room may offer an occupant more choices to avoid annoyance than do many offices. In some hotel rooms, though, various annoyances may coexist. A fan-coil unit may make noise, control temperature poorly and add odors to the room. Behind each source of discomfort lies a conscious choice of a product and its functioning, as shocking as that might seem. By what rules would you, as designer, avoid these pitfalls? Would you use personal judgment, product by product? Would you ask some potential occupants? Would you turn to guidelines that pertain to comfort?

GUIDELINES

Some formal guidelines (or standards) exist about how to achieve comfort or control discomfort. These include guidelines for the noise from exhaust fans, for distribution of illumination throughout a room, for transmission of noise across walls, for ventilation, etc. Guidelines should accomplish such goals as: 1) "transparency" of the environment, such that the occupant takes no notice of warmth, of the presence of odors, of the occurrence of intrusive noise, etc.; 2) facilitation of human functioning, e.g., reading efficiently; and 3) acceptable trade-off between subjective costs and benefits, such that the of noise from a bathroom fan seems an acceptable penalty for desired functioning along another dimension, the clearance of moisture.

In general, guidelines: 1) adopt an intuitive model of comfort, and 2) pay little or no attention to the existence of guidelines outside one modality. Regarding the first point: By the intuitive model, comfort derives strictly from physical conditions, a convenient fiction. By the intuitive model, human beings also simply reject any discomfort, another fiction. The intuitive model accepts individual differences between people as given and consequently without need for explanation. Indeed, the model often seeks to make a virtue out of the vice of ignorance by the use of disparity between people as the metric of comfort. A standard may deem a space comfortable when 20% of occupants find it uncomfortable and 80% find it comfortable. It takes little imagination to recognize that an explicit model might incorporate a parameter to account for why people might differ and might derive a different metric of discomfort. Regarding the second point: Guidelines for, say, the noise from a fan may ignore the thermal comfort-discomfort of an occupant on the grounds that noise is noise and heat is heat, and the difference ought to be just as obvious to the occupant as to the those who frame guidelines. The auditory modality may show no physiological interaction with the thermal modality, but in fact a hot-noisy environment may seem decidedly less comfortable than just a hot environment or just a noisy environment. For other sense modalities, such as chemoreception and thermoreception, obvious interaction may occur, as when hot, humid air appears more contaminated than cool, drier air.

The intuitive model of comfort unfortunately adapts poorly to failure. If a guideline fails to predict comfort well, then corrective action will seem necessary in more precise or elaborate physical measurement, rather than incorporation of a nonphysical variable. For those who assume it, the intuitive model seems less a model than reality. Some guidelines do predict comfort poorly in their domains and more elaborate measurement fails to fix errors. The intuitive model also makes no commitment regarding discomfort from more than one source.

DIAGNOSIS OF DISPARITIES

How one views comfort scientifically can determine how to address issues that arise when guidelines fail. Even when merely required to articulate a view of comfort, as opposed to assuming that everyone knows what it means, an investigator will deal with it differently and inevitably better.

Guidelines are commonly based in laboratory data. For example, recommendations for the amount of air necessary to dilute contaminants created by human occupancy have come from measurements of how visitors to chambers perceived occupant-generated odors. Field data on degree of acceptability among occupants of offices may fail to comport with predictions.

There is a temptation to place the burden for the disparity on the field work by the principle that field measurement lacks the precision of laboratory measurement. Were the environmental conditions in the field comparable to those in the laboratory? Rarely will that be so. Laboratory studies may exert precise control over the physical variables, but rarely will the laboratory study mimic the complexity of the field.

Were the same questions asked in the field as in the laboratory? Rarely were they. Field investigators pose more questions than laboratory investigators (e.g., How often do you get headaches? How comfortable is your chair?) and usually ask occupants to integrate their complaints over time (e.g., the past week, month, or year). Laboratory investigators understandably ask participants to integrate over just seconds or minutes. Such temporal disparities can invalidate comparisons. When asked to report complaints over the past month, occupants give a rate several-fold higher than if asked about just the present. The rate will also typically exceed that predicted by the chamber data.

Perhaps the most serious <u>apparent</u> limitation of the field data lies in the tendency for occupants in the field to carry "excess baggage" that leads them to embellish their complaints. Occupants, who are typically employees in the spaces investigated, are thought to use surveys opportunistically to vent their feelings about their status within the organization or their satisfaction. One might go so far as to see the outcome of such a survey as invalid for conclusions about comfort.

Field investigators, noting such problems, have episodically tried to address them in better surveys and, in some cases, bigger surveys with more participants. The "better" surveys may fail to produce appreciably better outcomes. People in the field still seem "too symptomatic" for their results to reflect actual environmental conditions. Perhaps the answer lies not in poor comparability between laboratory conditions and field conditions. Perhaps it lies not primarily in the technical details. Perhaps it lies in the unarticulated, typically intuitive model of comfort of the investigator.

THERMAL COMFORT STANDARD

Standards set by engineers tend, not surprisingly, to view comfort intuitively and operationally. Comfort may reflect itself in a simple vote, a rating. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has a detailed standard for thermal comfort (ASHRAE 55-1992): "The purpose of this standard is to specify the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space" [p. 3]. The standard deals with how such environmental factors as temperature, thermal radiation, humidity, and air speed, and such personal factors as activity and clothing interact to achieve thermal comfort. Perusal of the standard indicates tremendous potential complexity in the thermal environment. Although most laymen may think only about dry bulb temperature as the physical determinant of thermal comfort, a day in an office with a strong asymmetric solar load may cure that, as may a few hours in a space with a large floor to ceiling gradient in temperature. In neither case will the traditional setting on the thermostat ensure comfort.

The ASHRAE thermal comfort standard is both the prototype and the most interesting of the comfort standards or guidelines. Real-time measurements of the relevant physical parameters (dry bulb temperature, humidity, small- and large-field radiant temperature, air motion, skin temperature, air velocity, insulation of clothing) have long been feasible. Furthermore, there have been numerous laboratory studies of thermal comfort through the decades. Despite the advantages available to the thermal comfort standard, it can fail to predict field results. Does the problem lie with the physical measurements, psychophysical measurement, or elsewhere?

CONSTRUCTS

Most of us may think we could readily agree on a definition of comfort. ASHRAE's standard defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment" [p. 3]. From the standpoint of behavioral science, this definition is awkward. It is in part mentalistic, since it invokes the concept mind, and in part behavioristic, since it includes expression, a behavior. We can say, We all know more or less what we mean by these words. Can't we just move on to the measurements?

Before we proceed, we need to consider the concept or, more appropriately, the construct of comfort. This in turn requires consideration of constructs in general. Comfort reflects the same kind of reality as constructs such as love, honesty, pride, and numerous other intangible states that we generally agree exist, for we see them as regularities in the world. We know these regularities in their manifestations and, in a sense, create them to explain the regularities. When behavioral scientists have sought to study states and processes that lack tangible reality, they have sometimes created hypothetical constructs. Anxiety and intelligence are two well-known examples. Anxiety refers to intense fear or dread that results from no specifiable cause or threat. Much of pathological behavior results from the presence of anxiety or the inability to cope with anxiety .Hence, its "explanatory" role.

Intelligence refers generally to a capacity to learn and apply knowledge, but what kind of knowledge? We have all met people who seem both to us and others quite intelligent, but who might seem hopelessly inept at anticipating the needs of others, who might have appalling social skills, who might lack rudimentary mechanical aptitude, who might never be able to "find the open man" in a basketball game, or who cannot keep time with a beat. What then do we mean by intelligence? It obviously has something to do with intellectual competence, but we presumably weight some aspects of competence as more relevant than others. Is the ability to anticipate the needs of others via their facial expressions irrelevant? Perhaps not, but from what laymen have generally been taught about intelligence, it is not as important as abstract reasoning. It is also not the sort of talent that one could put on a paper-and-pencil intelligence test.

Should we then define intelligence in terms of the kinds of tasks one can put on paper-and-pencil tests? Should we redefine intelligence as "that aspect of intellectual competence that intelligence tests measure?" If so, intelligence tests would serve little purpose except vanity and sport. Those who score high would deserve respect to a degree commensurate to those who score high in pinball or Game-Boy games. In fact, we expect more. We expect predictive validity from them. We expect them to predict performance in school, for example, and they do, though rather modestly.

Among other things, intelligence tests do not measure motivation. As we all know, and probably take some comfort in, a person of modest measured intelligence and high motivation might perform better academically than a person of high measured intelligence and low motivation. What is motivation? As an impulse that incites to action, it is, as you may have guessed, another hypothetical construct. Hence, in order to understand academic performance, we have to understand at least the interaction of one construct with another. Unlike intelligence, which apparently stays stable over long periods, motivation fluctuates. Even if we agreed that we could assess its current level by some paper-and-pencil test, motivation measured outside the challenges of academic reality may have little predictive validity.

When the makers of academic aptitude tests, which are intelligence tests of a sort, look at the association between academic performance and scores on their tests, they are more or less satisfied. They can assess a huge sample of students where other factors, such as motivation, tend to balance out, though probably not entirely. (Low academic aptitude can kill academic motivation.) The test-makers also know, however, that schools vary in their demands. A grade of A in one school or even in one department often comes with much more work than in another. Accordingly, there is really no single perfect indicator of success. Even if the tests were, by some magic, perfect, there would be no way to discern so.

And so it will go. Behavior occurs in situations that are multidimensional and multi-determined. The constructs used to represent states (e.g., intelligence and motivation) are imperfect. Interactions between constructs add, in a way, potentially many complexities. Within this context, we wish to predict the future, e.g., academic performance over four years of college, or success in life, or something so comparatively simple as comfort.

THE CONSTRUCT OF COMFORT

Why do we care to measure comfort? We do so because we presumably believe that it mediates productivity. Comfort, no matter how defined, costs money to achieve, but presumably some level of comfort justifies the money in economic benefits. This accounts in part for why more American office-workers work in air-conditioned buildings than live in air-conditioned houses or apartments. Why have a construct of comfort? Can it do what the construct intelligence does?

A more broadly based construct of sensory comfort will, we hope, open possibilities for research and ultimately better understanding and predictions of comfort. It seems wise to "back into" the construct of comfort via a definition of sensory discomfort. Although comfort is the goal, discomfort, as the more motivating of the two states, should lead to action. It is the error signal that we wish to reduce to a negligible value. Under appropriate circumstances, we can define sensory comfort as the absence of sensory discomfort.

The field of indoor air quality, one might allege, has been in crisis over the inability to see connections between effects and their causes, between symptoms and their environmental determinants. Engineers, industrial hygienists, and "building specialists" of various types seem able to avert or abate problems by good housekeeping and good maintenance, but the professionals will often confess that they do not know what in particular they did that "solved" or averted a problem. We can take some solace in this outcome, but many problems remain unaverted or unabated. Without knowledge of cause and effect, investigations of buildings and the design of spaces can be a crap shoot. A construct of comfort that goes beyond the intuitive model may shift the odds in favor of understanding.

Let me propose a definition of sensory discomfort. (Why use the adjective sensory? Because there exist other forms of discomfort, such as the discomfort of waiting too long to be seen for an appointment.) Sensory discomfort is a state that a person attributes to unwanted sensory stimulation and that abates quickly with suitable adjustments in the magnitude or quality of stimulation. The definition, good or bad, has some consequences: The person may attribute the discomfort to sensory stimulation correctly or incorrectly. For example, the person might decide that a room that feels warm has poor air quality. In that way, and in many others, the person interprets the stimulation. So, even weak stimulation of a certain quality or periodicity might cause discomfort. More than that, the discomfort of yesterday or last week may sensitize the person. Everyone who has ever done an investigation into a problem with the indoor environment knows that respondents may inflate judgments of discomfort based upon how much they feel abused or ignored. Before going further into the determinants of discomfort, let me indicate the reason for the clause “that abates quickly with suitable adjustments in the magnitude or quality of stimulation.” It distinguishes discomfort from disease, which characteristically outlasts the inciting event.

To summarize to this point: 1) The example of the hotel room reminds us that comfort has multiple determinants many of which we experience in places specifically designed for comfort. Some people might weigh acoustic discomfort more heavily than thermal discomfort, etc., but true comfort depends on the integrated effect of various dimensions of stimulation. 2) Guidelines for comfort deal with one variety of stimulation (e.g., noise) and characteristically measure one aspect of discomfort (e.g., perceived noisiness) as its sole manifestation. 3) Guidelines of comfort usually deal with the physical determinants of comfort, treating the residual as statistical noise. This can be limiting because failures to predict comfort may inappropriately suggest the need for better physical measurement. The failures may also tempt investigators to blame respondents for giving distorted information. 4) Comfort is neither a thing nor a process, but a construct. Its determinants lie both within the physical world and within the person. To give an example from the domain of environmental noise, people who live near airports complain about noise more frequently than lab studies indicate they should from the characteristics of the noise. Why? Because these people fear that planes may crash into their homes. Such knowledge alters the research agenda about noise. It suggests the need to incorporate a construct of fear of a crash.

MODELING COMFORT

How should we frame the research agenda for comfort? From research in recent decades, we may know various fundamental determinants of comfort (see Levin, 1995). We do not know inter alia rules of integration. Fortunately, in the past two decades, research in behavioral science, business, economics, and medicine has developed a methodology called structural equation modeling (SEM) to explicate such rules (see, e.g., Schmmacker and Lomax, 1996; Raykov and Marcoulides, 2000). An entity called the latent variable forms the core of structural equation modeling, sometimes known as latent-variable analysis. We know the latent variable by its more generic name, construct. Comfort is a construct, just as are honesty and health, and gravity. As abstract summaries of some regularity in nature, constructs become scientifically pliable through a connection with concrete, observable entities or events. We cannot measure a construct itself, but only manifestations that lead us to discern its functionality.

In general, no single manifestation can define a construct or latent variable. How many measures of outcome would it take to define honesty or health, for example? Certainly more than one. The number one decides upon requires a theory. One could decide that honesty reflects itself in whether a person returns a wallet with its contents intact. Would that discern the level of honesty of the person of considerable means versus the poor mother who cannot afford medicine for her sick child? Undoubtedly not, so you would choose other observable variables as well, such as whether a person repaid a small debt that the lender had forgotten, whether a person told the truth when enticed to lie, or whether a person accurately listed hours-worked on a time-sheet. So it is with comfort. One does not measure it per se, one measures manifestations of it. One will virtually never suffice. Does this mean that ratings of comfort would not suffice to measure comfort? It does indeed, for virtually no single measure has the reliability or validity to reflect any construct. This does not mean that ratings would not provide a very good index. This may seem a limitation, but in fact it offers opportunity.

The accompanying diagram illustrates a hypothetical model for comfort written in notation of SEM, though actually leaving out some elements for simplicity. It may appear complicated, but consider at first only a piece (upper right-hand corner). The model indicates that the latent variable HealthStatus (of a person) has an effect on the latent variable AirQ (comfort with respect to the air). In this illustration, AirQ represents a perceptual rather than a physical variable and it manifests itself in the variables PercQual, which could be a rating, Symptoms, and Stuffiness. Within the context of this model, HealthStatus manifests itself via a diagnosis of allergies (Allergy) and a history of airway disease (HxAirwayDis), and via answers to questions on a standardized instrument known as the Quality of Well Being (QWellBeing) (e.g., Kaplan, Anderson, & Wingard, 1991; McDowell & Newell, 1996). (Before use of HealthStatus in the model, measurement would need to establish its legitimacy as a latent variable, not a trivial matter, but a necessary piece of business.) Whereas HealthStatus may affect AirQ directly, it may also affect AirQ indirectly via another latent variable Vulnerability, which manifests itself via an index of occupational status (OccupStatus), a demographic variable that may reflect age and sex (Demograph), and rated susceptibility to, say, colds-flu-sinusitis (Susceptibility). By now it should be clear that in the diagram every latent variable has three outcome variables. This has no particular meaning, except to indicate the need for more than one. Furthermore, the outcome variables need not come from the same domain. They may be objective, such as ratios of illuminance to define glare (Glare), may come from existing models, such as Perceived Noise Levels (NoiseLevel) (see Kryter, 1996), may entail performance, such as visual acuity (Acuity), or may involve subjective ratings, such as thermal comfort votes (ComfortVote).

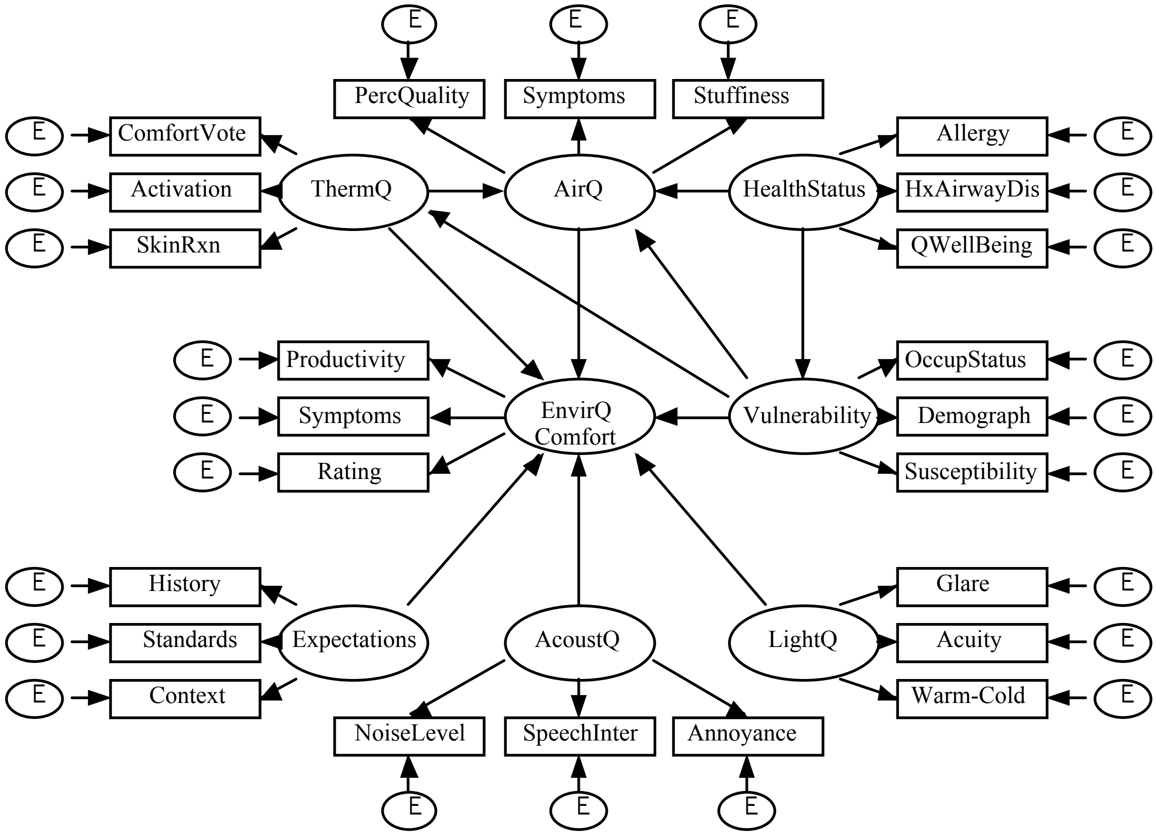

Figure 1. The schematic shows a model for comfort in the format of structural equation modeling (SEM) where arrows between variables reflect anticipated quantitative associations. Within the notation of SEM, ellipses represent latent variables (constructs) and rectangles represent measured or outcome variables. The ellipses with E's indicate the error associated with each measured variable. To illustrate, the skin (SkinRxn) may indicate vasoconstriction in cold and vasodilatation in heat, but nothing in between, which would mean that it fails to capture thermal comfort (ThermQ) between certain extremes.

The model can also accommodate situational factors in the form of latent variables, here illustrated with the Expectations, that would allow for context, such as whether a region uses air-conditioning (Context), in the assessment of net comfort (EnvironQ–Comfort). In the interest of simplicity, the model shows no arrows between Expectations and the various domains of comfort (ThermQ, AirQ, AcoustQ, LightQ). As indicated earlier, the intuitive model of comfort adapts poorly to failure. This happens in part because it fails to anticipate a role for variables such as Vulnerability and Expectations. Such variables should not become the trash bin for noise. They must have as solid a basis as any other latent variable.

Does Figure 1 represent merely some visionary's view of how research on comfort could occur in an ideal world with infinite resources? Hardly. It exemplifies various matters, including the following:

1) Comfort is a construct that exists in our thinking and cannot be measured directly.
2) Assessment of a construct requires more than one expression (outcome variable) for valid measurement.
3) A model of a phenomenon, such as comfort, may productively view and assess interaction between constructs.
4) Thinking about the interaction and manifestation of constructs encourages development of hypotheses, the engines of scientific progress.

5) There exists statistical methodology to test models of relations between constructs.
6) The new models can move research beyond the intuitive model of comfort.

The diagram in Figure 1 makes no commitment regarding the best measures for the latent variables, nor does it imply that this particular model will or should ever exist. It merely charts territory. Human comfort, despite its relevance to everyday welfare and functioning, receives proportionally little research attention compared, for example, to diseases. A search of PubMed (U. S. National Library of Medicine), a database of journal publications since the mid-1960's, indicates existence of a few hundred studies of human comfort (e.g., 277 of thermal comfort, 195 of annoyance from noise). Only relatively rare diseases have fewer than 10,000 studies. More common diseases, such as breast cancer and diabetes, have well over 100,000 each. When President Nixon declared war on cancer three decades ago, few could have envisioned that by the beginning of the 21st century more than a million studies of cancer would have ensued. Such numbers teach us that understanding takes time, effort, and optimism that we can solve even very complex problems.

CONCLUSIONS AND IMPLICATIONS

We should feel the need to progress from the state where discomfort represents just an unfortunate combination of physical factors to one where health status, vulnerability, and expectations, as handy examples, and any other relevant construct plays a role. No such construct, or latent variable in the terminology of SEM, comes into play by mere wishful thinking. It must earn its way through studies of reliability (stability) and validity (substantive relevance). We can know, however, that by erection of an explicit model of comfort we will inevitably find useful hypotheses to test and may find ourselves creating constructs as important to indoor environmental science as intelligence has been to the assessment of human abilities.

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