Toward Jeffersonian research programmes in ergonomics science

KIM J. VICENTE*

Cognitive Engineering Laboratory, Department of Mechanical & Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, Ontario M5S 3G8, Canada

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Thomas Jefferson believed that scientific research could lead to a fuller understanding of nature, while simultaneously addressing a persistent social problem of national or global interest. The two-fold ideals of this 'Jeffersonian research programme' fit well with the inherently practical aims of ergonomics science. However, in the past, basic and applied concerns have not always been well integrated in the discipline. This article makes a contribution, by proposing a novel metascientific framework consisting of a two-dimensional research space that addresses this problem. One dimension is methodological, representing the trade-off between experimental control and representativeness, while the other dimension is intentional, representing the trade-off between knowledge- and market-oriented purposes. The framework helps explain why it has frequently been difficult to integrate basic and applied concerns, and, at the same time, it shows that a Jeffersonian research programme for ergonomics science can be achieved by opening up degrees of freedom for research that have been comparatively unexplored. The importance of demonstrating contributions to fundamental understanding and to applied practice within the same research programme may be essential for survival and success in a climate of restricted research funding.

1. Introduction

Ergonomics science is different from some other disciplines, because it is inherently practical. One of its ultimate goals is to design sociotechnical systems that lead to improved safety, productivity, and worker health. Thus, generalizability to industry-scale problems is a central consideration. At the same time, however, ergonomics science should also be concerned with fundamental research questions. Otherwise, cumulative and unified knowledge—the hallmarks of scientific progress—will be hard to come by. Considerations of practical use and the quest for fundamental understanding have traditionally been referred to as 'applied' and 'basic' research, respectively. Using these terms, one can state that both applied and basic research have important contributions to offer the ergonomics science community.

Unfortunately, it has proven to be very difficult to solve practical problems and contribute to fundamental understanding at the same time (Rouse 1985, Meister 1989). Although the boundary between practice and theory is admittedly a fuzzy one, there seems to be an inherent tension between applied and basic concerns. The motivation for this article is that this tension has yet to be resolved in a productive manner by the ergonomics science community. Somehow, one must be able to

* e-mail: benfica@mie.utoronto.ca

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develop research programmes that respect the unique benefits of applied and basic research without letting one dominate the other. The purpose of this article is to propose a novel metascientific framework that can foster research that contributes to the enhancement of fundamental understanding as well as the resolution of practical problems in ergonomics science. Following the noted historian of science, Holton (1993), I will refer to this type of research as the 'Jeffersonian research programme' in honour of Thomas Jefferson's appreciation for research that led to a fuller understanding of nature, while also addressing a persistent social problem of national or global interest (Koch and Peden 1993).

How can ergonomics science achieve the two-fold aims of a Jeffersonian research programme? The framework proposed in this article shows that there are alternative ways of conducting research that have been relatively unexplored, and that, by exploring these alternatives within a single research programme, it is possible to contribute simultaneously to both basic and applied concerns. That there is a need for such a framework can be illustrated with a simple case study from research on translucent human–computer interfaces.

1.1. *A case study: translucent human–computer interface design*

Because of the prevalence of graphical user interfaces (GUIs), computer users have to interact with many different objects, such as text menus, tool palettes, and overlapping windows. As a result, it is not at all uncommon to find that these interface objects can obscure underlying images or text that are also of interest to users. For example, figure 1 shows a tool palette obscuring a substantial portion of an under-

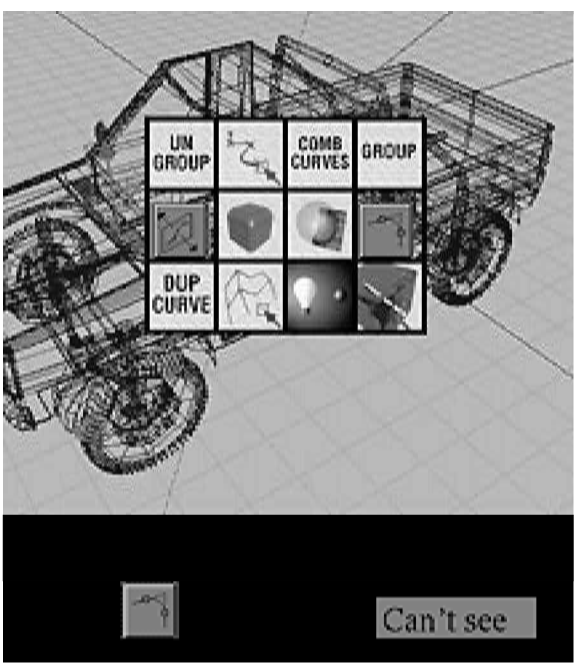

Figure 1. A sample image from a study of interface translucency by Harrison *et al.* (1995b). An opaque tool palette obscures an underlying wire frame object. Reprinted from Harrison *et al.* (1995b), © 1995 ACM, Inc. Reprinted by permission.

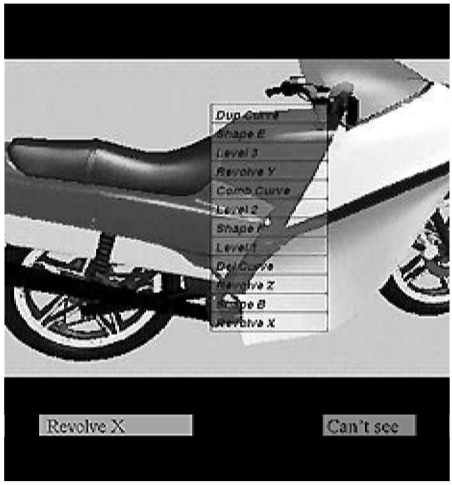

Figure 2. A sample image from a study of interface translucency by Harrison and Vicente (1996a). A translucent menu can be seen over an underlying solid object. Reprinted from Harrison and Vicente (1996a), © 1996 ACM, Inc. Reprinted by permission.

lying wire-frame image. Users may be interested in viewing the obscured portion of the image while the interface object is still on the screen. In such cases, users wind up spending a great deal of time managing these interface objects (e.g. moving palettes back and forth, resizing windows, opening and closing menus). These activities are overhead tasks, in the sense that they do not directly accomplish productive work (e.g. creating a 3-D model of an object). Therefore, one unintended side-effect of a GUI-style interface is that users are not as productive as they otherwise might be if they were able to spend more time on the central domain task of interest.

Harrison and colleagues (Harrison *et al.* 1994, 1995a, b, Harrison and Vicente 1996a, b) addressed this problem by designing translucent human–computer interfaces. An example is shown in figure 2, where a translucent text menu is superimposed on a solid object. With this type of design, it is possible for users to divide their attention between the foreground (i.e. the text menu) and the background (i.e. the solid object) at will, without having to engage in wasteful overhead activities. However, to optimize the design, it was necessary to determine an appropriate level of translucency. If the foreground object were too opaque, it would not be possible to see the background object to accomplish domain tasks because the object would be covered up. Conversely, if the foreground object were too translucent, it would not be possible to see it to accomplish domain tasks because it would not be legible. The optimal translucence point represents a trade-off between these two factors, allowing users to focus effectively on either foreground or background, as needed.

Harrison and Vicente (1996a) conducted an empirical study to determine this optimal translucency point for text menus like that shown in figure 2. The menus consisted of 12 commands (e.g. Revolve X, Revolve Y, Revolve Z, Dup Curve, Comb Curve, Del Curve). In designing their experiment, Harrison and Vicente were faced with the question of whether to keep the position (and, thus, the order) of the commands in the menu constant across trials, or whether to vary the position of the commands randomly across trials. Computer menus in commercial software have a fixed order, which suggests that the first option is more appropriate because it is representative of the conditions that users would encounter outside of the laboratory. After all, results with randomly varying menu items could not be expected to generalize to the normal case of fixed order. Perhaps surprisingly, Harrison and Vicente decided to vary the position of the commands randomly across trials, despite the fact that this situation is not representative. Why would they make such a counterintuitive choice?

The purpose of Harrison and Vicente's (1996a) experiment was to investigate the impact of translucency on the legibility of the text in the foreground layer (see figure 2). To obtain a sufficient number of data points for statistical analysis, participants were given many trials of practice at the task. Therefore, if the position of the commands on the menu was kept constant across trials, then it is possible that participants might memorize the position of each command with practice. Under these circumstances, participants would be able to perform the task accurately without even reading the text on the menu. For example, if Revolve X was always the top item on the menu, then participants might be able to select this item merely by clicking on the top of the menu, even if the text was illegible due to a high level of translucency. This possibility was inconsistent with the experimental goal of assessing the impact of translucency on text legibility. Thus, Harrison and Vicente (1996a) adopted the counterintuitive choice of randomizing the position of the commands in the menu across trials because it better served the objectives of their experiment.

This simple example shows that the conflict between experimental control (to obtain a fundamental understanding of phenomena) and representativeness (to solve practical problems) can be subtle, even in the seemingly most straightforward of cases. Furthermore, recognizing this subtlety can lead to research decisions that are, perhaps, counterintuitive from other perspectives. Thus, it is important to try to understand better the complex relationship between basic and applied concerns.

1.2. *Outline*

The remainder of this article is organized as follows. First, a methodological continuum of research with experimental control on one end and representativeness on the other will be described. The concept of representativeness was originally defined by Brunswik (1952: 30) as follows:

> The study of functional organism–environment relationships would seem to require that ... situational circumstances should be made to represent ... conditions under which the organism has to function. This leads to what the writer has suggested to call the 'representative design of experiments'.... Any generalized statement of relationship requires specification of a 'reference class' or 'universe' from which the material is drawn.

This definition implies that representativeness is always relative because research must explicitly be representative of some reference class. In the case of ergonomics science, the reference class is usually the set of work situations to which one wants to generalize research results. Note also that representativeness has several dimensions (e.g. work domain, scenarios, tasks, social-organizational structure, participants). A study that is representative along one dimension may not be on another. Nevertheless, for the purposes of this article, it is sufficient to discuss representativeness as if it were a unidimensional construct. Secondly, an intentional continuum of research with a knowledge-oriented purpose on one end and a market-oriented purpose on the other end will be described. Thirdly, these two continua will be used to create a novel metascientific framework consisting of a two-dimensional research space. This framework will show that ergonomics science has tended to focus on certain areas of the space and has relatively ignored other areas. Finally, the implications of this framework will be discussed, showing that it is possible to attain the two-fold benefits of a Jeffersonian research programme by conducting research in the unexplored areas of the aforementioned research space and by adopting a methodologically diverse research programme.

2. A methodological continuum of research

Part of the tension between basic and applied research concerns is well captured by Hammond's (1989) Law of the Laboratory, which states that 'rigour is inversely related to representation of complexity' (p. 2; see also Cook and Campbell 1979). This fundamental trade-off in empirical research can be used to create a continuum of research types with highly controlled, but unrepresentative investigations on one end and highly representative, but uncontrolled investigations on the other end (Vicente 1997). Figure 3 illustrates this continuum along with four prototypical research types. In ergonomics science, as well as psychology, much more emphasis has been given to the controlled but unrepresentative end of this continuum. This historical trend can be noted by briefly describing the four categories in figure 3. Note that both the continuum and the four types are not intended to be exhaustive or unique. There are many other ways to categorize research. Nevertheless, these distinctions are useful for the purposes of this article.

2.1. *Types of research*

2.1.1. *Type 1—highly-controlled laboratory experiments*: These studies use simplified tasks and either hold constant, or independently manipulate, each factor that may be relevant to the phenomenon under study to obtain an unconfounded understanding of the effect of each independent variable.

An outstanding example is the work of Gould *et al.* (1987). These ergonomics scientists sought to isolate a single-variable explanation for why people read more slowly from CRT displays than from paper. To achieve this goal, they conducted 10 experiments, each of which tried to isolate the impact of a single independent variable. The conclusion obtained from this sequence of 10 studies was that the reading speed difference between CRT displays and paper is likely due to a combination of variables, probably centred on image quality. The fact that this highly-controlled, reductionistic research was awarded the Jerome H. Ely Award for the outstanding paper published in volume 29 of *Human Factors* shows that this type of work was highly valued by the ergonomics science community.

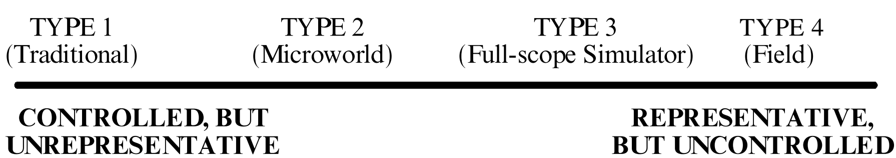

Figure 3. A methodological continuum of research showing the trade-off between experimental control and representativeness (adapted from Vicente 1997).

2.1.2. *Type 2—less-controlled but more complex laboratory experiments*: These studies do not explicitly try to control for every factor, but instead present participants with more complex tasks than Type 1 research. Most microworld research belongs in this category, the idea being to have some experimental control and some representativeness as well, thereby improving the chances of generalizability to operational settings.

A particularly representative example is the 6-month-long, longitudinal study of ecological interface design conducted in a process control microworld by Christoffersen *et al.* (1996, 1997, 1998). Participants were only told what the task goals were, not how they should achieve them, so that the impact of interface design on participants' strategies could be assessed. As a result, participants sometimes controlled the microworld in qualitatively different ways, even within interface groups. In addition, equipment failures were modelled in the simulation to mimic the risk present in industrial processes, albeit on a much smaller scale. Thus, an inappropriate action by a participant would cause a component to 'blow up', prematurely ending a trial. Because different participants experienced a different number of such 'blow ups', the number of trials they completed and the amount of time they spent controlling the microworld differed. Furthermore, single and multiple component failures were unexpectedly introduced into the simulation at pre-defined times to investigate participants' ability to manage disturbances. However, the participants did not have the microworld in the same state or configuration at the times when faults were introduced, so the impact of any one fault could differ substantially across participants. In the extreme case, if the participant was not using the failed component, there would be no disturbance for them to detect, diagnose, or compensate. For these and other similar reasons, this experiment was much more representative of industrial process control than a typical laboratory experiment, thereby enhancing the generalizability of results. However, a price was paid in terms of a concomitant decrease in experimental control. Because of all of the uncontrolled variability, it was not possible to develop a rigorous, causal explanation for the results that were obtained over the course of the study. Despite these limitations, many novel hypotheses were generated and some of these have since been investigated in more controlled laboratory studies (e.g. Hajdukiewicz and Vicente 2000).

2.1.3. *Type 3—evaluations conducted in high-fidelity simulators*: These studies try to increase representativeness further with the hope of increasing generalizability to operational settings, but give up a great deal of experimental control as a result.

A good example is the investigation of safety parameter display systems (SPDSs) conducted by Woods *et al.* (1982). They investigated the impact of two different SPDSs on the performance of professional, licensed operators in a full-scope nuclear power plant simulator—a very representative, albeit simulated, setting. Data were collected for 16 complex accident events, representing the types of disturbances that can be experienced in a commercial nuclear power plant. Because of the strong representation of realism, many variables were not controlled for and there was a great deal of variability in the data. As a result, 'the study was not able to provide quantitative results in answer to the question of how much of an impact the SPDS will have on operator performance' (Woods *et al.* 1982: S-10). Nevertheless, qualitative data analyses of the decisions made by the operators revealed important insights into the impact of the SPDSs on operator strategies. The fact that this study is still cited as a notable example of how to conduct a full-scope simulator study illustrates the impact that it has had on the literature.

2.1.4. *Type 4—descriptive field studies*: These studies are concerned with observing and documenting highly representative behaviour in the field, to obtain a better descriptive understanding of naturalistic phenomena. Usually, there are no independent variables because it may not be possible to manipulate any factors in a systematic fashion during actual work conditions. Consequently, there is no experimental control at all.

An influential example is the field study of maritime navigation conducted onboard a US Navy ship by Hutchins (1995). Because of the naturalistic nature of the investigation, Hutchins was not able to manipulate any variables in a systematic fashion. He had to be content to study the idiosyncratic events that the sailors happened to be faced with during his observation periods. Thus, there was no experimental control whatsoever, meaning that it was not possible to conduct any rigorous tests of competing hypotheses. This did not stop Hutchins from making a scientific contribution. On the contrary, his descriptive field study methodology allowed him to make novel, creative observations about the nature of cognition in the wild. These insights are quite different from those that had been obtained by cognitive scientists who had studied cognition in the laboratory. Even more importantly, Hutchins' work has had a tremendous impact on several disciplines, leading to more controlled studies in cognitive science (e.g. Zhang and Norman 1994) and analogous field studies in ergonomics science (e.g. Vicente and Burns 1996). These studies have deepened our understanding of distributed cognition.

2.2. *The traditional view*

How have these types of research been traditionally viewed in the ergonomics science community? It is always difficult to characterize people's attitudes to very broad issues without being accused of presenting a straw man position. To side-step this criticism, this study will deliberately present a caricature of what is perceived to be the traditional view.

2.2.1. *Type 1—highly-controlled laboratory experiments*: In the traditional view, this is 'real' science. It is purported to be the only reliable way to discover fundamental principles that are pure in the sense that they are not tied to any particular context. In the words of Banaji and Crowder (1991: 79), 'If you wish to do research that is useful (i.e. practical, functional) the *optimal* path is controlled experimentation' (see also Shiffrin 1996).

2.2.2. *Type 2—less-controlled but more complex laboratory experiments*: These are poorly designed experiments. Because some factors are not meticulously controlled for, the results are confounded. Doherty (1993: 362) frankly described the traditional aversion to this type of research: 'I still have the deep intellectual and emotional attachment of the experimental psychologist to the simple, single variable experiment'.

2.2.3. *Type 3—evaluations conducted in high-fidelity simulators*: In the traditional view, this research will not lead to the discovery of scientific laws because the study is not conducted in a 'pure' manner. In the words of Kelso (1995: 32): 'most naturalistic behaviour is too complicated to yield fundamental principles'.

2.2.4. *Type 4—descriptive field studies*: This research is not considered to be scientific, because usually no factors are manipulated by the experimenter (orthogonally or otherwise). Thus, it is not possible to isolate the causal factors that are responsible for the phenomenon of interest. Furthermore, there is usually a great deal of variability in the data, so even in the rare cases where it is possible to conduct statistical tests, they rarely yield significant findings (Baker and Marshall 1988). Therefore, in the traditional view, findings from this type of research are considered to be highly subjective and completely speculative.

2.3. *Alternative views*

Critiques of this comparatively narrow view of science are hardly new (e.g. Brunswik 1956, Chapanis 1967, Gibson 1967/1982, Lorenz 1973, Neisser 1976, Sheridan and Hennessy 1984, Meister 1989). In fact, the limitations of the traditional view have been recognized by an increasing number of ergonomics scientists in recent years, probably because research emphasizing experimental control to the detriment of representativeness has not had much success in technology transfer to industry-scale problems (Rouse 1985, Meister 1989). As a result, there has been a counter movement to study human behaviour under more naturalistic conditions (Klein *et al.* 1993, Zsambok and Klein 1997). The rationale behind much of this work is that Type 1 research, as defined above, and in figure 3, does not generalize to experienced workers performing representative tasks under naturalistic work conditions. Thus, the naturalistic movement has increased the emphasis given to representativeness. Frequently, it has been concerned with Type 3 or Type 4 research. The hope is that research results will be more generalizable and that technology transfer to industry-scale problems will be more successful than in the past.

As shown in figure 3, microworld research can be viewed as a compromise between traditional, controlled research and naturalistic, representative research (Brehmer and Dörner 1993). It tries to capture some of the features of work settings (albeit in simplified ways), thereby enhancing the possibility for generalizability to operational settings, and, thus, technology transfer. At the same time, microworld research tries to include some experimental control (although less than traditional controlled experiments), thereby avoiding some of the threats to validity that usually plague simulator and field studies (Baker and Marshall 1988).

The author believes that too much emphasis has been placed on highly-controlled experimentation in ergonomics science, and that both naturalistic and microworld research have something important to offer. Having said that, there is a danger that these alternatives can be thought of as replacements for traditional research (Kirlik, in press). Hammond's (1989) Law of the Laboratory reminds one that there is a fundamental trade-off between experimental control and representativeness within any individual study. Therefore, any single point along the continuum in figure 3 represents a compromise with some advantages over other points, but, unavoidably, some disadvantages as well. As Kirlik (in press) has pointed out, this point is not always recognized by researchers who advocate naturalistic and microworld research. Thus, there is a danger that these alternative forms of research will replace traditional highly-controlled experimentation, resulting in a new set of limitations that are complementary to those of traditional research. As a step towards avoiding this risk, a second continuum of research is presented in the next section.

3. An intentional continuum of research

Scientific research is a very complex human activity, and so it can be classified in many different ways. The continuum in figure 3 is based on methodological considerations. Some readers may have interpreted the left (controlled) pole of the continuum as corresponding to basic research and the right (representative) pole of the continuum as corresponding to applied research. Note, however, that the terms 'basic' and 'applied' were never used in the previous section to describe figure 3. Thus, if some readers have interpreted the figure in this way, it is because they believe that the distinction between basic and applied research is a methodological one. The author believes that this view is unproductive because it leads to an overly restrictive view of research that fails to integrate basic and applied concerns (Vicente 1994). To see why this is so, it is necessary to classify research in a different way from that in figure 3.

Figure 4 illustrates a continuum of research that is based on intentional considerations (i.e. the main purpose that researchers had in mind at the time that they conducted the work). It was borrowed from the mission statement, circa 1994, of Risø National Laboratory in Roskilde, Denmark. Risø is a government research laboratory that is involved in multidisciplinary research, a small subset of which has been very influential in the ergonomics science community (Vicente, in press). Around 1994, Risø's stated objective was to further technological development in energy, environment, and materials. The results of Risø's research have been widely applied in agriculture, industry, and public services. The most relevant part of the mission statement dealt with the research profile of the laboratory. There, it stated that the emphasis was on 'long-term and strategic research providing a solid scientific foundation for the technological development of society'. Figure 4 is an adaptation of a figure that was used by Risø to graphically illustrate the emphasis of its research profile.

On the left end of the continuum, the primary purpose of the research is *knowledge-oriented*. The goal here is to answer questions of broad theoretical significance in a manner that leads to a principled understanding of the phenomenon being investigated. On the right end of the continuum, the primary purpose of the research is *market-oriented*. The goal here is to answer questions of very specific practical interest in a manner that leads to the resolution of an industry-relevant problem

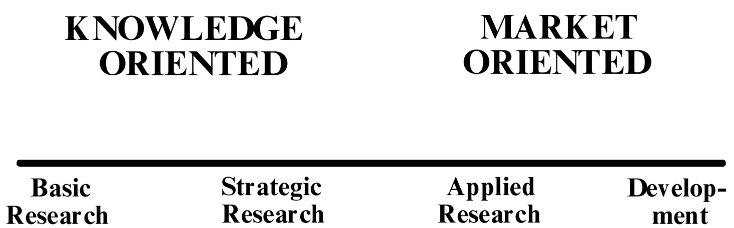

Figure 4. An intentional continuum of research showing the trade-off between knowledge- and market-oriented purposes (adapted from Vicente 1994).

being investigated. Note that no direction of flow is specified, because either type of research can inform and influence the other, a point that will be explored in more detail later. Risø identified four areas along figure 4 corresponding to different research types.

3.1. *Types of research*

3.1.1. *Basic research*: Basic research falls on the knowledge-oriented part of the continuum. In this case, the exclusive purpose motivating a study is to contribute to theoretical understanding. Note that such research may eventually have practical applications and lead to technology transfer to industry, but these pragmatic considerations are not the original motivation behind the research. In fact, in many cases, the practical implications of this type of knowledge-oriented research are unforeseeable.

3.1.2. *Strategic research*: Strategic research is still aimed at contributing to theoretical understanding, but it is also usually constrained by some market-oriented considerations. For example, in the case of the Natural Sciences and Engineering Council of Canada (www.nserc.ca), several scientific areas have been identified as being particularly important to the Canadian economy (e.g. biotechnology, energy-efficient technology, environmental technology, information technology, manufacturing and processing technology, and materials technology). Accordingly, targetted funding has been provided for strategic research that is aimed at these areas. Nevertheless, researchers are still expected to contribute to theoretical knowledge and publish their results in peer-reviewed publications in the scientific community.

3.1.3. *Applied research*: Applied research falls on the market-oriented part of the continuum. Here, more attention is paid to industry-relevant considerations. While some of this research can still be conducted in a university, it is explicitly targetted at technology transfer to industry rather than contributions to scientific theory. Accordingly, applied research is usually primarily evaluated, not based on journal publications, but on patents, spin-off companies, impact on commercially available products or services, and other such market-oriented criteria. Interestingly, however, this category is not the pole of the market-oriented part of figure 4.

3.1.4. *Development*: Development serves as the pole of market-oriented activities. Here, the goal is pragmatic to the point that the activities being conducted may no longer be classified by many as research. The goal of development is to design and build a product that is satisfying a market need. Frequently, this type of work cannot be published in scientific journals, either because the research is proprietary or because the insights gained are *ad hoc* and idiosyncratic, rather than principled and generalizable. In many cases, this type of work is (justifiably) conducted in industry rather than in academe.

3.2. *Conclusion*

The intentional continuum in figure 4 has a clean correspondence with the ideals embedded in the Jeffersonian research programme. To satisfy the two-fold purposes that were so valued by Jefferson, a research programme must be both knowledge-oriented (thereby contributing to the principled understanding of nature) and market-oriented (thereby contributing to the resolution of a persistent social problem of national or global interest). But, how is this possible? How can research be at two points along a single continuum at the same time?

A resolution to this conundrum can be obtained in two moves. First, one must change one's level of analysis. So far, a comparatively detailed level of resolution has primarily been adopted, focusing on an individual study as the fundamental unit of analysis. However, it is possible to adopt a more coarse level of resolution, focusing on a research programme comprising multiple studies as the fundamental unit of analysis. By making this change, one can obtain new insights. For example, one can see that Hammond's Law is only true for a single study. In that case, there is a fundamental trade-off because one experiment cannot be designed to maximize both experimental control and representativeness. However, if the level of analysis is moved to that of a research programme, this trade-off may be overcome. Similarly, it can be seen that the apparent conflict between knowledge-oriented and market-oriented aims only exists at the level of a single study. If the level of analysis is moved to that of a research programme, this trade-off can be overcome as well.

Secondly, one must clearly distinguish between the methodological and intentional dimensions represented in figures 3 and 4, respectively. Despite the fact that the two figures represent different dimensions, it may seem like there is a great deal of correspondence between the four categories of research in figure 3 and the four categories in figure 4. The reason for this apparent similarity is that researchers have not explored the full range of possibilities that are available to them. The rationale behind this claim will be explained next by adopting a morphological approach (Zwicky 1967), thereby showing that the continua in these two figures are actually orthogonal to each other.

4. A two-dimensional research space

One of the contributions of this article is to show that ergonomics scientists have tended to conflate the methodological dimension of research, represented in figure 3, with the intentional dimension, represented in figure 4. Figure 5 disambiguates these dimensions by presenting them as orthogonal to each other. The result is a two-dimensional metascientific space, with different areas corresponding to different types of research. A single study is represented as a point in this space because it adopts one particular methodology and was conducted with one primary purpose in mind. Accordingly, a research programme consisting of a sequence of studies is represented as a trajectory connecting together a number of points in the space. Figure 5 provides several important insights.

First, it can be seen why there has traditionally been a gap between so-called basic and applied research. In the behavioural sciences, at least, most academic research and corporate development have been conducted at diametrically opposite corners of the space. Thus, these activities have differed both methodologically and intentionally. Traditional academic research has been knowledge-oriented and highly controlled, but unrepresentative. Corporate development has been market-oriented and highly representative, but uncontrolled. No wonder the former has had a limited impact on the latter in terms of technology transfer.

Secondly, one can also see that there are certain areas of the space that have been comparatively unexplored, at least in the ergonomics science community. For instance, the upper left corner of figure 5 represents research that is market-oriented

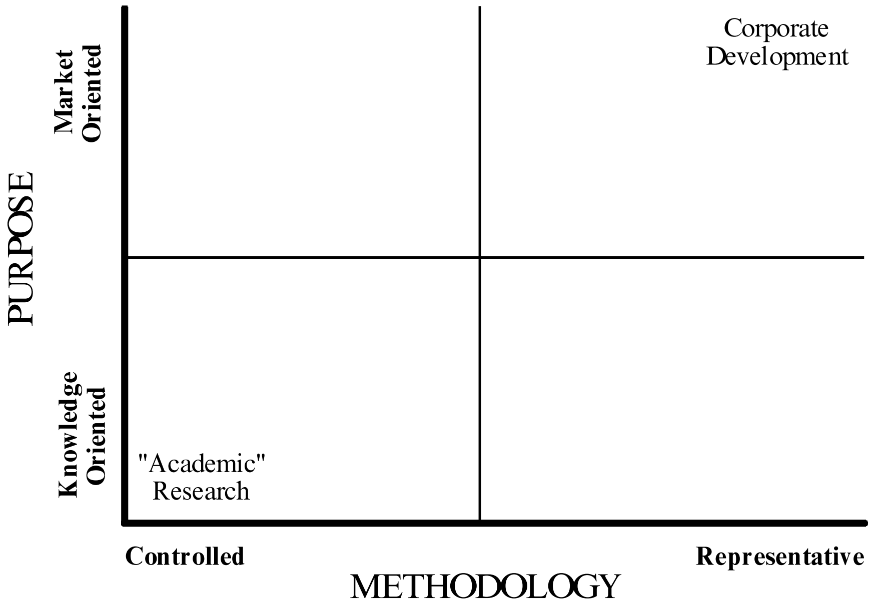

Figure 5. A novel framework consisting of a two-dimensional research space that is constructed using the two continua in figures 3 and 4.

and controlled, but unrepresentative. An example would be marketing research (e.g. a focus group) that is aimed at discovering what features potential customers might want to have in a consumer product. The benefit of this type of research is perhaps more obvious to the interests of industry (e.g. to determine what features should be eliminated from an overly complex design). However, as will be discussed below, this area of the space can also benefit academe. The lower right corner has also been comparatively unexplored, although recent research in naturalistic decision making is helping to fill this gap (Klein *et al.* 1993, Zsambok and Klein 1997). The interesting feature of this area of the space is that it explicitly shows that knowledge-oriented research can be conducted in the field, not just in the laboratory (Lorenz 1973, Woods 1993, Hutchins 1995). This fact contradicts the more traditional view that research that is conducted under representative conditions is inherently applied, a view that probably arises from a failure to distinguish between research methodology and research purpose. Figure 5 shows the limitations of such a view by showing that these two dimensions are actually orthogonal to each other.

Thirdly, and perhaps most importantly of all, the space in figure 5 also shows that research programmes can benefit from visiting different areas of the research space *in particular orders*. Several prototypical examples are shown as trajectories in figure 6. Beginning in the upper left corner, *market-driven* research can be initiated by a market need that has been identified by interviewing customers (e.g. identifying what types of information companies would like to have in their control rooms) and then subsequently using that need as a focus for conducting knowledge-oriented controlled experiments (e.g. on the technical properties of new sensors that could provide the desired information; cf. Reising and Sanderson 1996). Conversely, *market-discovery* research can be initiated by first conducting controlled experiments to contribute to understanding and then subsequently canvassing people in industry

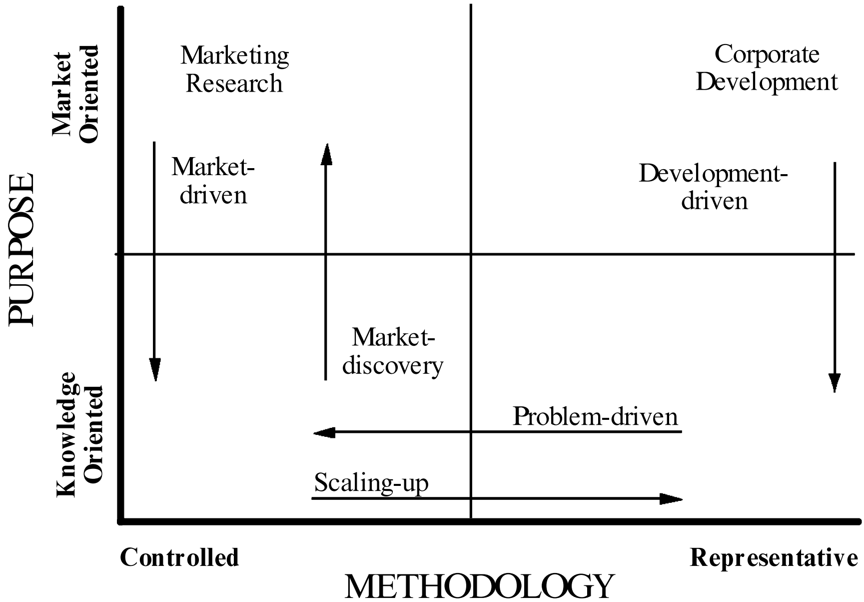

Figure 6. Types of research programmes that have been comparatively unexplored in human factors, mapped as trajectories in the space in figure 5.

to determine if the knowledge or technology that has been generated can satisfy an existing or future market need.

Moving to the bottom of figure 6, *problem-driven* research can be conducted by first observing and describing phenomena under naturalistic conditions to identify a research problem that is worth solving, and then subsequently conducting controlled experiments to understand the factors contributing to that problem in a rigorous manner. Conversely, *scaling-up* research can be conducted by taking the theories and results obtained from controlled experimentation and using them to design more representative but less controlled studies, to see if those theories and results generalize to situations that are typical of those encountered in the field.

Moving to the upper right corner of figure 6, *development-driven* research can be conducted by using corporate design activities as an opportunity to understand the fundamental principles that govern the interaction between people, technology, and work in the field (Woods *et al.* 1996). Although design activities are usually highly opportunistic and idiosyncratic, they do have the benefit of usually being highly representative. Thus, if the requisite time and resources are available, it may be possible to examine successive design iterations from a theoretical perspective to extract lessons learned that may be generalized to other contexts. Such principles would represent a contribution to knowledge because they would provide a theoretical basis for making predictions, for instance, about the impact of particular technological interventions on human performance *in situ*.

Figure 5 could probably also be used to map other types of research programmes, conceivably even for other areas of science and engineering. However, the prototypical examples traced in figure 6 should suffice to make the point. Ergonomics scientists have not yet made full use of the research opportunities that are available to them. This may help explain why an integration between basic and applied concerns has been hard to come by.

5. Implications

The key implication arising from figures 5 and 6 is that, by exploring several areas of the research space within the same research programme, it is possible to conduct research that contributes to a fundamental understanding, while also contributing to the solution of practical problems of social significance. In short, a Jeffersonian research programme for ergonomics science is a viable pursuit. To achieve this ideal, however, certain conditions must be met.

5.1. *Pre-conditions for a Jeffersonian research programme*

First, it is necessary to explore areas of the space in figure 5 that have typically been under-represented in ergonomics science. Several examples were given in figure 6 to show that these types of research can be put to good use. If one sticks to the traditional, diametrically opposed corners of traditional academic research and corporate development, then one is likely to keep getting what has been had in the past—an unfortunate gap between fundamental research and practical problems of social significance. For an inherently applied discipline like ergonomics science, this is an unacceptable state of affairs (Meister 1989). Opening up the degrees of freedom in research programmes can be of tremendous benefit by providing a tighter coupling between basic and applied concerns.

Secondly, there must also be methodological diversity within the same research programme. Ergonomics scientists have tended to stick to a consistent methodology within a research programme (e.g. a sequence of highly controlled experiments, or a sequence of naturalistic field studies). In doing so, they do not escape the limitations of that methodology, or conversely, they do not enjoy the complementary benefits of other methodologies. Through methodological diversity, we can overcome these problems and cut through Hammond's Law.

For instance, one model for a research programme that exploits the benefits of methodological diversity has been described by Sheridan and Hennessy (1984). Field studies can be used to observe behavior *in situ* to identify phenomena that are worthwhile studying under more controlled conditions. Laboratory studies can then be conducted under more controlled conditions to try and develop causal explanations for the observed phenomena. The generalizability of these causal explanations can then be tested under more representative conditions by conducting experiments that are complex in nature, say with microworlds. Finally, a theory or design intervention can be evaluated in high-fidelity simulators or in the field, in the presence of a wide range of factors that had been controlled for or eliminated in the laboratory, to see if the same results are still obtained.

5.2. *An example of a Jeffersonian research programme*

The research programme on translucent human–computer interfaces mentioned earlier is an example of the application of this model (Harrison *et al.* 1994, 1995a, b, Harrison and Vicente 1996a, b). Figure 7 shows the trajectory representing the sequence of studies that was conducted as a part of this Jeffersonian research programme.

The first (unpublished) phase was to observe users interacting with a commercially available 3-D modelling and paint application *in situ*, to identify a practical

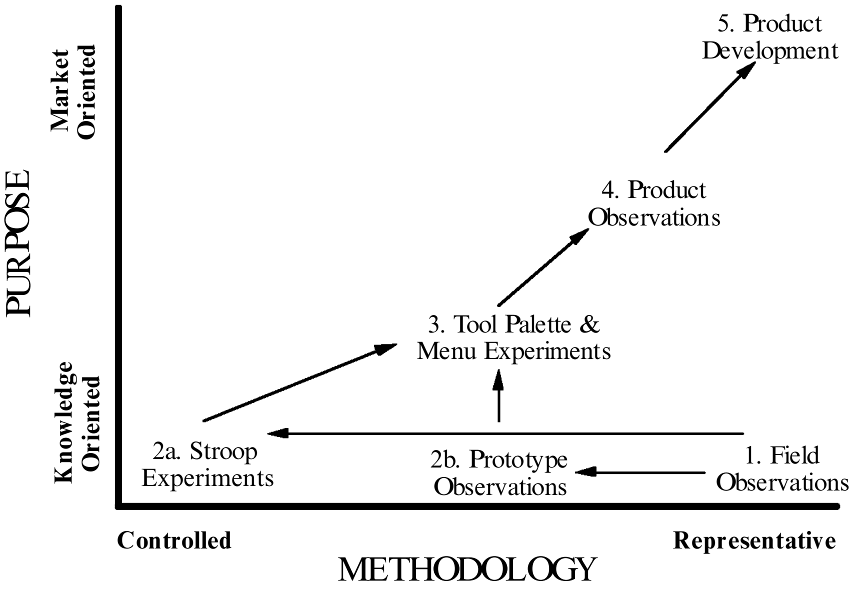

Figure 7. The trajectory approximately describing the process followed by Harrison and colleagues in their research programme investigating translucency in human–computer interface design.

problem that could serve as a worthwhile subject for knowledge-oriented research (point #1 in the space). Harrison and colleagues found that users spent a great deal of time managing interface objects rather than accomplishing productive work. This finding provided a focus for all subsequent research. The idea of using translucency to address this practical problem was generated, and two paths were followed in parallel to explore this option (Harrison *et al.* 1994, 1995a). On the highly controlled end, the impact of translucency on the Stroop (1935) effect was investigated experimentally (point #2a in the space). The Stroop effect is a well-known phenomenon that has been extensively studied in experimental psychology. In a traditional Stroop task, a series of words is presented in randomly chosen colours (e.g. red, green, blue, yellow). Participants must name the ink colour while ignoring the word. Some words are neutral (e.g. uncle, shoe, cute, nail), whereas other words are the names of conflicting colours (e.g. yellow, blue, green, red). Consistent, significant performance degradation occurs when conflicting colour words are used and participants attempt to name the colour of the ink (e.g. the word 'red' appears in green ink; the correct response is 'green'). In later studies, a consistent and significant Stroop effect was found even when the word was printed in black ink, presented adjacent to a colour bar. It is virtually impossible for participants to consciously block or prevent the Stroop effect in selective looking tasks. The idea was that this would provide a worst case estimate of the translucency level representing a balance between foreground and background legibility. If one could eliminate interference in the notoriously interference-prone Stroop task, then one would have a conservative estimate of the lower bound of translucency level that would be appropriate for more representative stimuli. Interestingly, this experiment made a novel contribution to fundamental understanding because the effect of transparency on the Stroop effect had never been investigated before, despite the fact that over 700 studies had been conducted using this paradigm (see MacLeod 1991 for a review)! At the same time, more representative interface prototypes were created to observe the effects of translucency with real images and foregrounds (point #2b in the space). These observations were conducted informally, thereby giving up experimental control. Nevertheless, they provided some useful fundamental insights into the impact of translucency on human performance in divided and focused attention tasks.

As shown in figure 7, the insights obtained from these activities fed into a third stage of research. The results from the Stroop and prototyping studies were used to design less-controlled experiments using more representative stimuli (point #3 in the space). One set of experiments was conducted to evaluate the impact of translucency level with typical tool palettes like that shown in figure 1 (Harrison *et al.* 1995b). Another set of experiments was conducted to evaluate the impact of translucency level with text menus like that shown in figure 2 (Harrison and Vicente 1996a). These studies were conducted, in part, to further understanding of the impact of translucency on human performance (a knowledge-oriented purpose), and, in part, to further understanding of how translucency should be implemented in commercial software products (a market-oriented purpose).

The results from these studies were used to modify an existing 3-D modelling and paint application so that it would incorporate translucency (Harrison and Vicente 1996b). A representative set of users was then asked to work with the product for a few weeks, and their reactions and experiences were recorded (point #4 in the space). A great deal of experimental control was given up, but the situation investigated was much more representative of work conditions. The primary purpose was to determine how translucency should be implemented in a commercial product, given the stringent limitations of the existing technology (a market-oriented purpose). At the same time, however, more was also learned about the impact of translucency on human performance under representative conditions (a knowledge-oriented purpose). Finally, the insights obtained from these observations guided a product development phase of work (point #5 in the space). Translucency was implemented in a new version of a commercially available 3-D modelling and paint application, thereby successfully completing the technology transfer cycle.

This type of two-fold contribution to fundamental understanding and to the design of a commercially available product is relatively rare in the ergonomics science literature. Although it is difficult to prove it, the author believes that this atypical success can be attributed, in large part, to the unique advantages of the Jeffersonian research programme that was adopted as a basis for this work.

5.3. *A pluralistic wrinkle*

The case study just described is only one model for achieving a tighter integration of theory and practice. Ergonomics science can only benefit from a pluralistic approach. Thus, to avoid any misunderstandings, it is important to point out explicitly that the Jeffersonian programme is intended to be broadly inclusive. For example, the integration of 'basic' and 'applied' concerns that have been focused on in this article need not occur within the work of a single individual. It could very well occur across the work of various individuals, some who are solely concerned with market development and others who are solely concerned with fundamental knowledge, for instance. In other words, not all ergonomics scientists need to be concerned with both market- and knowledge-oriented purposes. There is no reason why, in some cases, different individuals can not focus on particular areas of figure 5 where their unique skill sets can be put to greatest use. Having said that, at some point, someone has to take on the responsibility of bringing together the isolated contributions of such individual specialists for a particular area of research. Otherwise, Jeffersonian integration will not be achieved, and it will continue to be difficult to satisfy the two-fold objectives of ergonomics science.

6. Conclusions

This article has sought to clarify the distinction between basic and applied research in ergonomics science. A novel metascientific framework consisting of a two-dimensional research space has been proposed by explicitly separating research methodology from research purpose. The framework helps explain why there has not been a tight coupling between basic and applied concerns. More importantly, the resulting space also opens up degrees of freedom for research that have been comparatively unexplored. By making full use of various research methodologies within a single research programme, it is possible to realize a Jeffersonian research programme that contributes to fundamental understanding and practical problems at the same time. A case study on translucency in human–computer interface design provides a concrete example, showing that this type of work can lead to achievements that have been difficult to obtain using more traditional approaches to ergonomics science.

In closing, the author would like to emphasize a broader positive feature of the Jeffersonian research programme that goes well beyond ergonomics science. In times of scarce research funding, it will be increasingly important to demonstrate to the public and to government that scientists in every discipline can contribute to fundamental understanding and address considerations of use in the same research programme. As Stokes (1997: 81) put it:

> Freed from the false, 'either–or' logic of the traditional basic/applied distinction, individual scientists would more generally see that applied goals are not inherently at war with scientific creativity and rigour, and their overseers and funders would more generally see that the thrust toward basic understanding is not inherently at war with considerations of use.

Therefore, the Jeffersonian programme may be just what ergonomics science and other branches of science and engineering need to survive and succeed in the face of the stringent economic constraints that are sometimes imposed by science policy.

7. Postscript

Although the metascientific framework in figure 5 is novel, the general philosophy of a Jeffersonian research programme is not entirely new to ergonomics science. As a reviewer of this article pointed out, some of the best work in the discipline has already followed this general approach. A balanced attention to fundamental understanding and practical problems can be found in the research of several founding fathers of ergonomics science, including Broadbent, Christensen, and Fitts, to mention just a few. However, somewhere along the way, the value of this type of research seems to have been overlooked. Most contemporary research programmes in ergonomics science would not qualify as Jeffersonian. For this reason, it seems worthwhile to revisit the insights of one's founding fathers by providing an explicit metascientific framework that can help one obtain a fuller understanding of nature while simultaneously addressing a persistent social problem of national or global interest.

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About the author

Kim J. Vicente received his BASc (1985) in Industrial Engineering from the University of Toronto, his MS (1987) in Industrial Engineering and Operations Research from the Virginia Polytechnic Institute and State University, and his PhD (1991) in Mechanical Engineering from the University of Illinois at Urbana-Champaign. During 1987–1988, he spent 1 year as a visiting scientist in the Section for Informatics and Cognitive Science of the Risø National Laboratory in Roskilde, Denmark. During 1991–1992, he was on the faculty of the School of Industrial and Systems Engineering at the Georgia Institute of Technology. Since 1998, he has been professor of Mechanical & Industrial Engineering and of Biomaterials & Biomedical Engineering at the University of Toronto, and director of the Cognitive Engineering Laboratory there. He is also an adjunct professor of psychology at Miami University, Ohio, and a registered Professional Engineer in the province of Ontario. Currently, Kim serves on the editorial boards of the *International Journal of Cognitive Ergonomics*, *Human Factors*, and *Theoretical Issues in Ergonomics Science*, and on the Committee for Human Factors of the US National Research Council/National Academy of Sciences. He is also a Senior Fellow of Massey College. Kim is the recipient of several research awards, including the Premier's Research Excellence Award, valued at $100 000. He has authored or co-authored over 50 journal articles, and over 70 refereed conference papers. He is the author of *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-based Work*, published by Lawrence Erlbaum Associates.