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Technical Report

Computational Models of Human Performance

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COMPUTATIONAL MODELS OF HUMAN PERFORMANCE

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ABSTRACT

We describe advances in computational human performance modeling in two human factors domains: Workload prediction and display layout. In each domain, we describe the model parameters that can be easily quantified and those for which major challenges to quantification remain. We discuss the validation work that has been carried out so far.

INTRODUCTION

Our human factors profession often finds itself at a disadvantage when trying to lobby for the inclusion of human factors principles in complex system design. The reason for this is often the failure of the human factors engineer to be able to present hard numbers justifying the human performance costs or benefits of certain design features. The accountant can easily derive numbers reflecting the dollar cost of certain features; the engineer can often provide numbers describing, say, the weight or reliability of certain equipment specifications (although the error in the estimate of the latter may be much greater than indicated). The problem is that the human factors engineer just has principles... "you shouldn't put this design feature in because it violates the principle of S-R Compatibility." The project engineer then asks, "What will that violation cost in systems performance terms to make it worthwhile spending \$XXXX to change it?" Unfortunately, we rarely have answers. Our principles are usually expressed in words but not the numbers that can be balanced against the engineer's or accountant's numbers.

These numbers must be provided as the output of a computational model of human performance, as driven by system design. To get numbers out, however, we must also have a way of getting numbers in; that is, objectively quantifying features of an interface, a set of tasks or a set of displays in terms that matter to human performance. I'll talk today about the foundation and validation of such models in two related domains--workload prediction and display layout--reflecting a program of research funded by NASA's A³I Program. Special thanks go to Tony Andre, Ian Haskell, and Ken Sarno, along with a number of other students at the University of Illinois, who have contributed much of the thinking and data. In both domains, I shall identify the challenges of quantifying the inputs and of validating that the quantitative outputs to accurately predict human performance in multi task and multi display situations.

WORKLOAD PREDICTION

The first domain is that of workload prediction. Here we ask, "What quantifiable characteristics of a set of tasks contribute to the prediction of when performance will break down in multiple task situations--when the task demand exceeds the resource supply?" The logical starting point for such a model (and an easily quantifiable one) is simply to tally the number of tasks performed per unit time. Then, using the representation in figure 1a and b, we can clearly predict that the workload will be greater in (b), with an average of 1.3 tasks/unit time (130% workload) than in (a) with time only 40% filled with task demands. All we need for such a model is estimates of mean task times, and such data are readily available from a number of sources.

However, what is missing from this model is an estimate of task demands. Shown on the right side of the figure are two additional time lines (Figure 1c and 1d). Here the increased thickness of each task bar represents the added difficulty of a task, which may vary independently of the time it takes; consider, for example, the difference between a 5-minute flight segment in light and heavy turbulence. A time measure of workload will show (a) and (b) to be equivalent to (c) and (d), respectively, but we know this not the case. Collectively, the results of research we have done at Illinois (Wickens, Larish & Contorer, 1989; Sarno & Wickens, 1991) has shown that the incorporation of task demand level into a time-line model will bring the variance accounted for, in predicting differences in performance of a set of multiple task configurations, from near zero up to around 60%.

But the issue of how to quantify task demands (other than by their time) is a challenge. For example, how do we quantify how much more difficult it is to remember seven digits than five? There are table look-ups (Aldrich, Szabo & Bierbaum, 1988) and there are possibly also some fundamental metrics based on information theory or working memory load which can be used. This is certainly a challenge for future research.

A second feature missing from a quantitative-computational model is an accounting that certain tasks interfere with each other more than others; not because their demands are greater but because of their similarity to each other. The pilot can fly and listen to communications simultaneously more easily than he or she can talk and listen. There are several factors, of course, that influence this structural similarity between tasks (Wickens, 1992). We have identified these in terms of three structural dichotomies in the information processing system. Do tasks share the same stage of processing (both perceptual/cognitive, or both responding)? Do they share the same perceptual modality (both auditory or both visual); and do they share the same processing code (both verbal/linguistic, or both spatial)? This resource-sharing factor can be fairly simply implemented in a computational scheme by imposing a penalty of 1, 2, or 3, depending upon the number of dimensions shared between a pair of time-shared tasks. Ken Sarno's research has found that a more elaborate similarity-based computational scheme, based upon North and Riley's (1988) "WINDEX" model, can predict a great deal more variability between different task configurations than can a pure time-line model, and somewhat more variability than can a demand-based model (Sarno & Wickens, 1991).

A final feature that should be incorporated in a computational workload model is one which accounts for how people schedule, shed, or add tasks when workload becomes excessive (Shankar, 1991). What little evidence we do have in this domain is enlightening, because it suggests that people deal with overload situations by adopting fairly simple rules of task-shedding rather than more complex optimization schedules (Raby, Wickens & Marsh, 1990; Moray, et al., 1991). The real challenge to computational models will be to identify (and predict) the level of demand at which concurrent task performance "catastrophically" regresses to sequential performance (Figure 2).

The summary, presented in table 1 then indicates my feeling of where we are in the quest for a computational model of multiple task performance, the promising avenues for quantification, and the challenges. The last item in the table is one that we have not yet discussed, but which leads us directly to the second domain of computational models. This is the issue of how time-sharing is affected by the separation of displays.

FACTOR	CHALLENGE	SOURCE
Time Line	Task Time Data	Boeing, HOS
Demand level	Task Effort Data (Table Lookup)	McCracken/Aldrich
Multiple Resources (Similarity-based Interference)	Simple Conflict Matrix	WINDEX, CREWCUT
Scheduling/Shedding	Simple Rules and Algorithms	Z-scheduler/CREWCUT
Display Separation	Cost of Info Access Effort	Visual Scanning Models

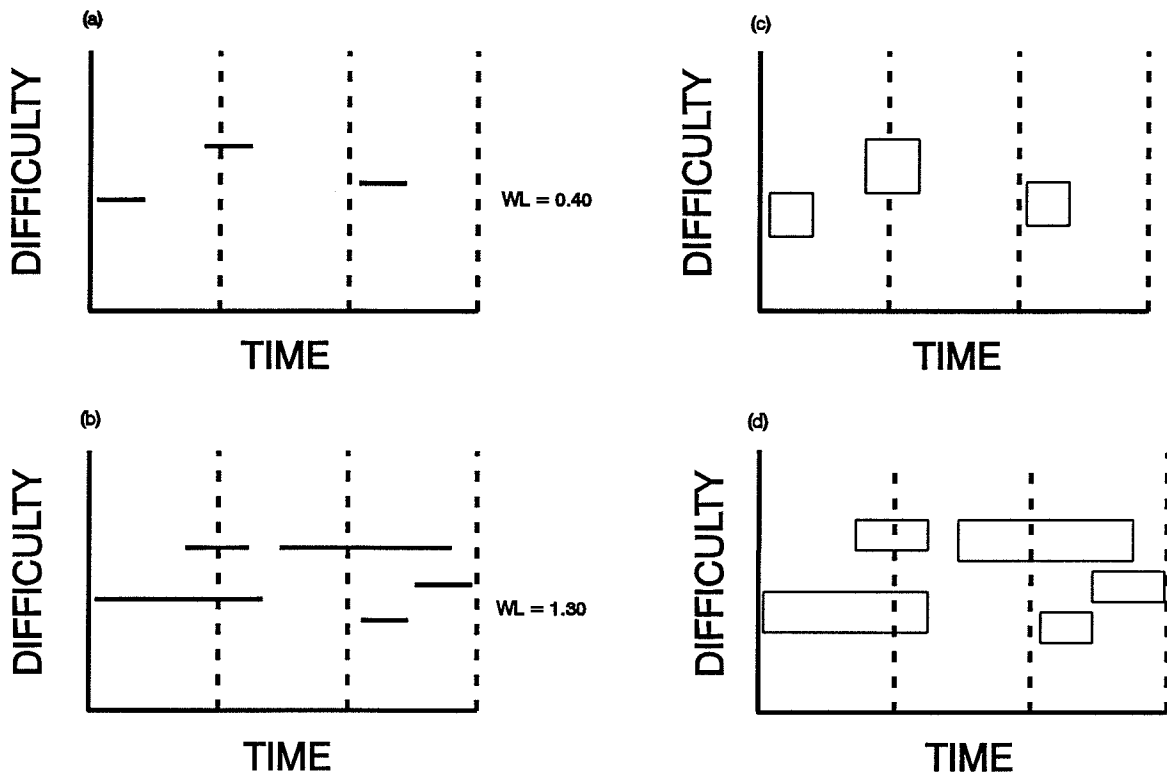


FIGURE 1: TASK TIME LINE ANALYSIS

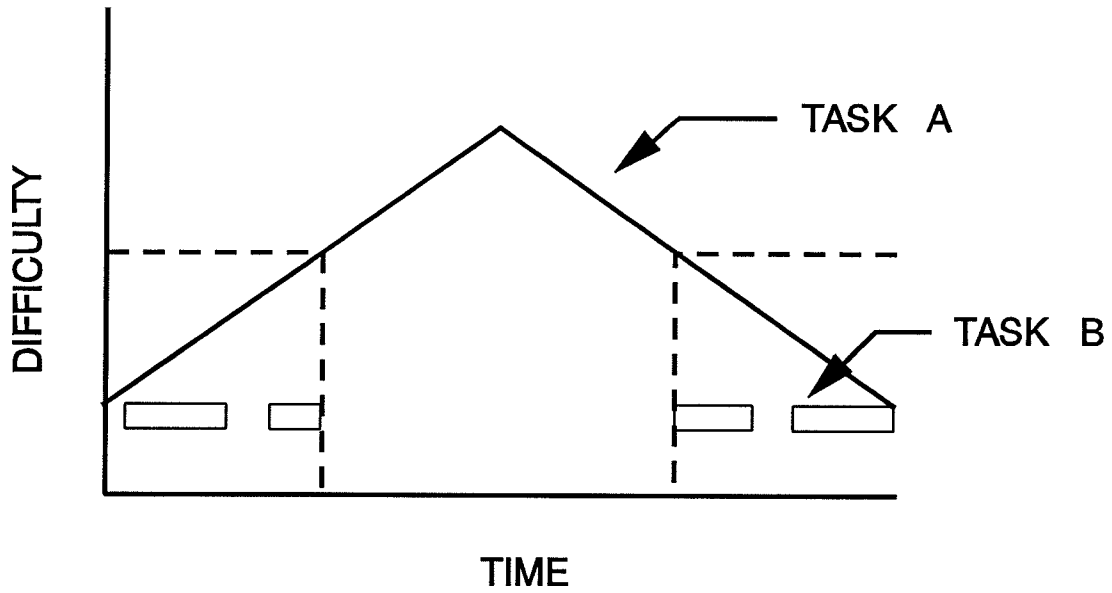


FIGURE 2: TASK (B) SHEDDING WITH DIFFICULTY CHANGES IN TASK (A).

DISPLAY LAYOUT ANALYSIS

A good computational model should be able to guide the display panel designer to consider the costs and benefits of positioning different sources of information at different locations (Prevost and Banda, 1991), so this will influence the efficiency of either performing a single task that must rely upon different information sources (an altitude change or coordinated turn, for example, both require integration across instruments), or performing multiple tasks within a similar time window. Below, I will describe what I see as the fundamental components of such a model, adding layers of complexity as we go along, each "layer" being related to some underlying principle of human performance. I also hope to show the source of numbers that may be used to quantify that principle.

IMPORTANCE AND PROXIMITY. To begin with, it is obvious that any given display should be available to foveal vision. If we deal with only one display, this becomes trivially simple to arrange. However, if there are two displays (in the typical aircraft setting, we can consider one "display" as the forward view out the windscreen), then what we are describing, by the need to foveate, is a design "force" based on the economy of human information processing that attracts the two displays toward each other (Figure 3). At its simplest level, we might imagine this force as proportional to the importance of the two displays (the frequency with which they are used) and their distance apart, as reflected in the formula at the bottom of the Figure [$F = D[I_1 + I_2]$]. Quite readily, a number can be assigned to distance (degrees of visual angle) and, with a little more effort, to "importance" as, perhaps, reflected by a count of how often the two displays are fixated. With such a computation on each pair of displays, an overall "figure of merit" could then be derived for the ensemble by averaging these forces across all pairs (Andre & Wickens, 1991).

What, then, are the principles of human information processing that "drive" this desire for proximity between two displays? We identify five below, and suggest, where possible, the basis of quantitative data that could underlie a computational model of these forces.

INFORMATION ACCESS EFFORT. The first of these is what I call information access effort and accommodates that most important, effortful mechanism of visual scanning. Display pairs that are located quite close together (within a few degrees) can both be consulted without scanning. This "No Scan Region" is often equal to the fovea but will also vary as a function of the visual angle of symbols that need to be resolved, and it will be larger if motion perception is required than if the task calls for symbol classification (Anstis, 1974). That is, we can recognize larger symbols at greater eccentricity. Quantitative data on these sizes may be found in handbooks (Boff & Lincoln, 1988). When two displays are separated by an angle that exceeds the no-scan region so that a visual scan or saccade is necessary, evidence suggests that the time and effort required for longer scans are not much greater than for short scans (Liu & Wickens, 1992). This scanning takes place within a region that Sanders (1970) has labeled the "eye field." However, if the separation is greater than an angle which the eye can easily scan without head movement, then head movement will add an extra

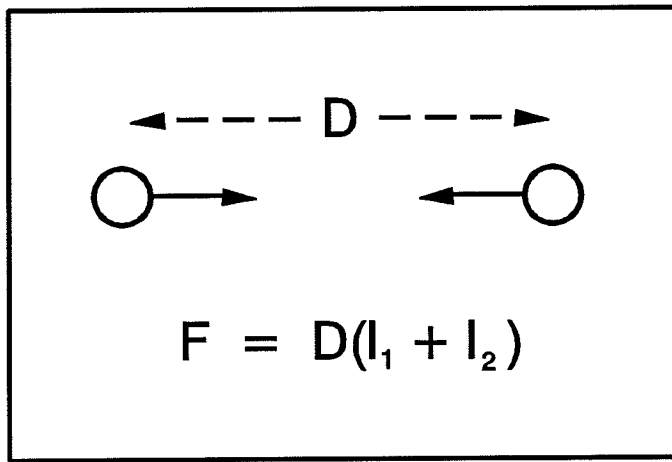


FIGURE 3: DISPLAY ATTRACTOR FORCE.

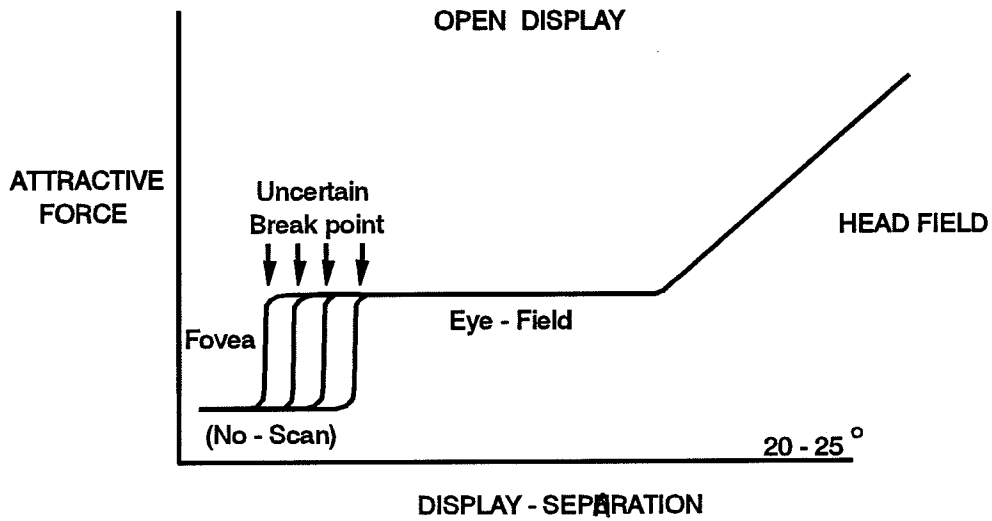


FIGURE 4: INFORMATION ACCESS EFFORT ACROSS THE VISUAL FIELD.

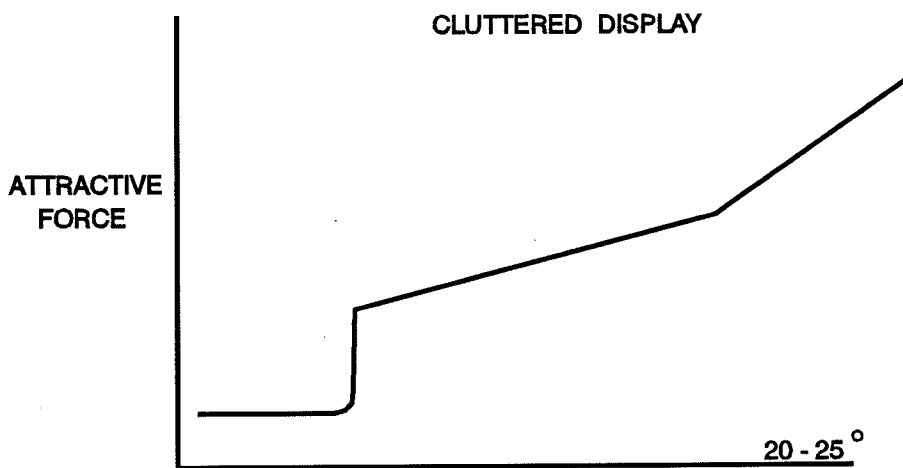


FIGURE 5: IAE IN A CLUTTERED DISPLAY AS A FUNCTION OF DISPLAY SEPARATION.

penalty of effort. Unlike eye movement, we propose that this penalty grows in magnitude proportional to its distance, since, unlike visual saccades, head movements are not ballistic. Collectively, these information access factors are proposed to be reflected as the penalty function shown in Figure 4. Equivalently, Figure 4 might also be thought of as an "attractor" force function. The break point from the no-scan region to the eye field will depend upon the resolution requirements of the information sources; between the eye field and the head field, the discontinuity has been estimated to fall at around 25° of visual angle (Sanders, 1970).

SEARCH UNCERTAINTY. The function depicted in Figure 4 has assumed an open field between the two information sources and, indeed, we have found that in such an open field, changes in the visual angle between information sources have little effect on performance within the eye field (Wickens & Andre, 1990). However, in a cluttered display, the same investigation revealed an increasing penalty with longer distances. As the eye must scan from one destination to the next, it becomes progressively more difficult to locate the target destination, as the intervening field is filled with greater "clutter" of other nontarget objects, a well-known finding in the research on visual search (Teichner & Mocharnuk, 1979). Eye movements are also initiated more slowly if their destination is uncertain and inconsistent (Liu & Wickens (1992). To accommodate this effect of uncertainty of search location, which is amplified in cluttered displays, Andre & Wickens (1991) have proposed the concept of a linear "object distance" penalty which may be computed by the number of visual objects that must be scanned from origin to destination. Alternatively, assuming a homogeneous density of display objects across the scanned space, this penalty may be considered a linearly increasing function of metric distance. Hence, for a "cluttered" display, the attractor function of Figure 4 may become more similar to that shown in Figure 5.

CONFUSION. When scanning across a multi-element display, the effect of the "attractor force" depicted in Figure 5 would be to bring all displayed elements to a single, superimposed location, much, as matter is attracted to a "black hole." Clearly, the consequences of this mass attraction, shown in Figure 6, would be *tragic and* counterproductive because of the confusing picture created by superimposed images. Hence, we must identify a "repeller" force of constant magnitude between all displays that will increase as a function of their proximity beyond a certain threshold (Figure 7). Such a force will serve to keep displays separated unless their attraction is extremely strong (as is the case with head up displays, to be discussed later).

Recently, we have collected data that appears to reveal quite clearly the collective effects of the forces shown in Figures 4 and 7 (Martin-Emerson & Wickens, 1992). Subjects tracked a cursor at the top of the display screen and were simultaneously required to make a rapid visual discrimination between arrows which were presented at various degrees of the visual angle below (Figure 8). The latter task, while intermittent, required foveal vision, while the continuous tracking task could be continuously carried out (although with degraded quality) in peripheral vision while the eye was fixated on the arrow. The range of visual angles between the two displays, from superimposition to 36° separation, accommodated both eye and head fields. Performance data on the arrow reaction time task shown in Figure 9 shows a pattern

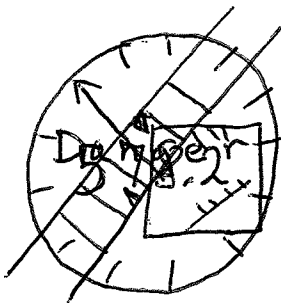


FIGURE 6: THE TRAGIC CONSEQUENCES OF TOO MUCH ATTRACTION.

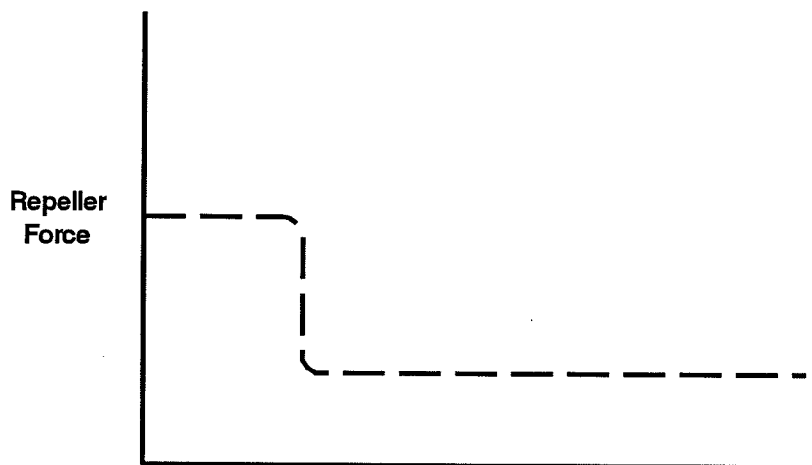


FIGURE 7: THE REPELLER FORCE TO PREVENT FIGURE 6.

FIGURE 8

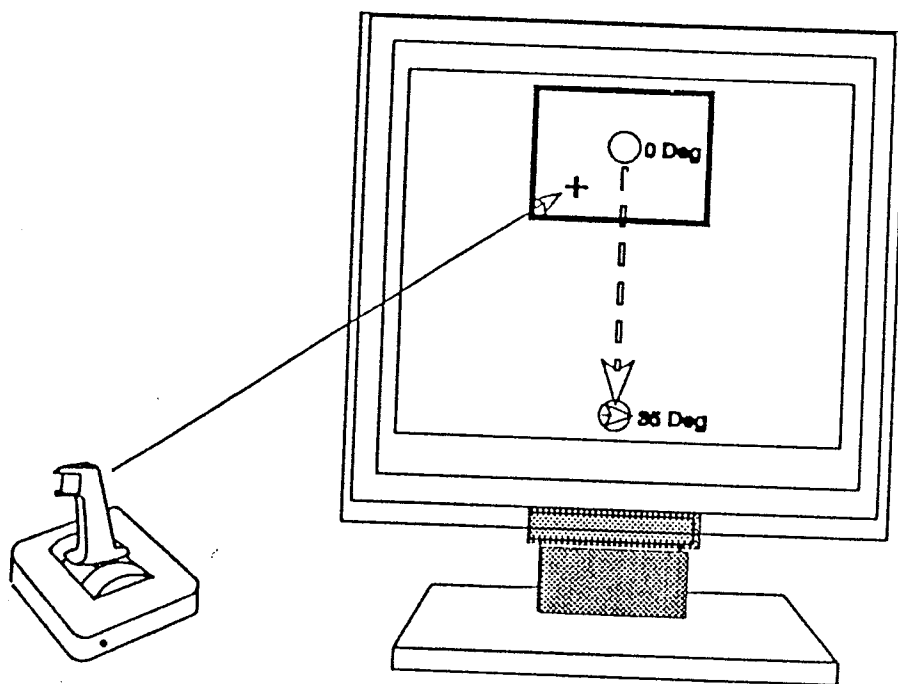


FIGURE 9

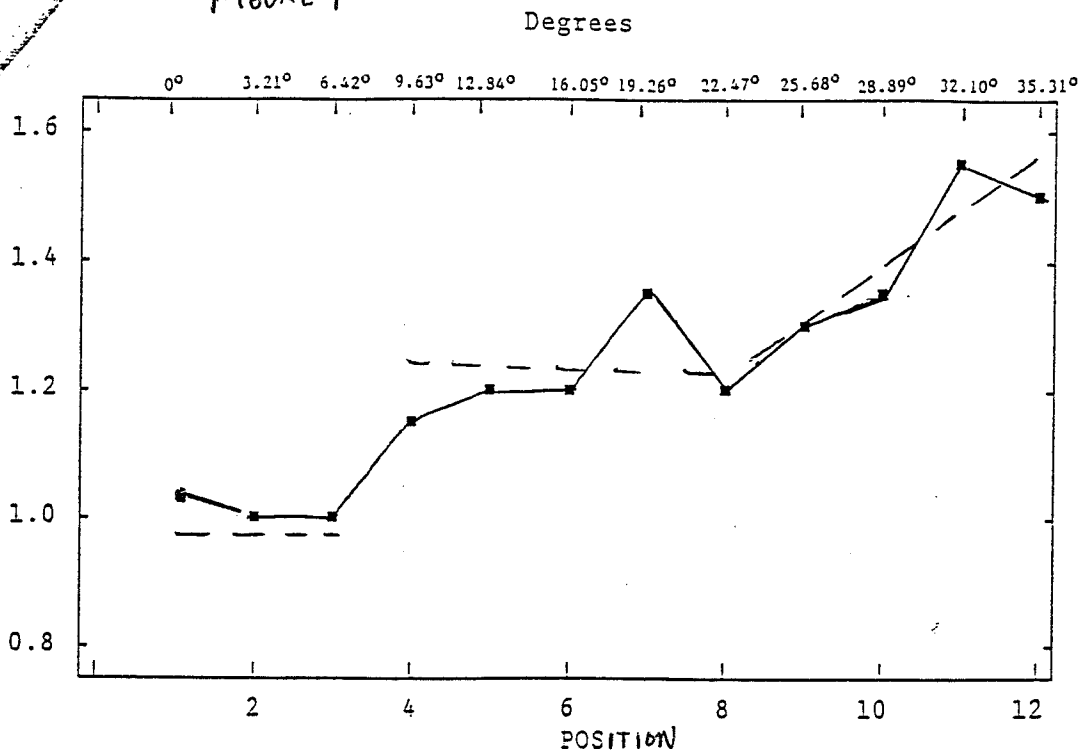


Figure 9: Mean reaction time as a function of position corresponding to degrees vertical separation of stimuli.

that is quite consistent with the open field aspect of the model shown in Figures 4 and 7. At the smallest angle (superimposition), the benefits of no scanning are more than offset by the cost of confusion from overlapping images. Hence, best performance occurs at the smallest angle where there is no superimposition. A step increase in RT is realized when scanning becomes necessary (at 4.5°), but no further increase is shown until an angle of around 24° when we assume that the head field is reached. (The high latency point 7 is a distortion due to first-trial order effects.) The head field induces then, a proportionately increasing penalty for progressively greater head movements. The data for tracking errors are similar, but here the penalty is a linearly increasing one beyond 4.5°. We infer that this cost is increasing through the eye field, not constant, because of the increasing loss of motion information resolution that is manifest at progressively larger visual angles of eccentricity (Levison, Elkind & Ward, 1971).

RELATEDNESS. The data shown in Figure 9 would imply that true superimposition of images as in the head up display or HUD is a bad idea, and that a small separation is desired. However, much of the information that is presented on a HUD has a special quality that makes superimposition desirable: The information is said to be conformal with the world beyond, upon which it is superimposed. In other words, it is directly related to that world, and the intent of the display is to better allow the pilot to integrate these two sources of superimposed information.

This example leads us to consider a fourth "force" that should moderate the forces depicted in Figure 7. Sources that are related to each other (or are to be integrated in a common task) should experience a stronger mutually attracting force. Elsewhere, we have described this differential force in terms of the Proximity Compatibility Principle (PCP) (Wickens & Boles 1983; Carswell & Wickens, 1987; Wickens & Andre, 1990). Two or more information sources that need to be mentally integrated (close task proximity) should be displayed with close "psychological proximity" (e.g., common color, belonging to a single object, proximity in space). This defines the concept of "proximity compatibility." Information sources that are to be distinct from each other should be displayed more separately. In support of this view, Martin-Emerson & Wickens, (1992); found that the cost of increasing separation, shown in Figure 9, was enhanced if the arrow stimuli were relevant to the tracking display. For the current discussion, our measure of display proximity is, of course, that directly measured by object distance (or metric distance in a multi-element display). However, the precise definition of task proximity is somewhat more difficult to achieve. There are certain circumstances where two indicators must clearly be integrated or compared--a command and actual air speed indicator, for example; or altitude and vertical velocity indicators when approaching a new flight level. In these two cases, task proximity is quite high and the attractors will be strong. But there may be other circumstances when two indicators are related to the same task but do not need to be integrated; for example, cross checks between heading and altitude on a coordinated turn. Their task proximity is less. Also, it is unclear what sort of proximity force should attract two indicators that pertain to the same system but may rarely be used in sequence, let alone integrated (e.g., two warning lights pertaining to different aspects of the same component).

Notwithstanding this uncertainty, the important attraction force of task relatedness was clearly demonstrated by Andre in his recent dissertation (Andre & Wickens, (1991). Andre designed a set of eight cockpit display layouts, such as that shown in Figure 10, that varied in their adherence to guidelines of keeping functionally related displays grouped together, and keeping high priority displays close together (using the formula shown in Figure 3). For our discussion here, the important contrast was between performance of subjects using the layout that adhered to functional grouping while violating importance organization, and those pilots flying the with converse arrangement (i.e., keeping frequently fixated displays close, but separating functional groups). The contrast convincingly demonstrated that performance with the former layout was better, and other aspects of data analysis consistently revealed that adherence to priority-based grouping, while important, had less of an impact on the overall figure of merit of the display-task interface than did adherence to functional grouping.

The application of computational metrics to quantify adherence to grouping principles was made somewhat easy in Andre's experiment because he was able to clearly define coherent task-related clusters on the basis of flight task analysis. Hence, grouping was quantitatively measured by the dispersion of displays within each cluster from each other. In fact, however, in many display situations, the unique membership of displays in such clusters is far less clearly defined, nor is it always clear, as described above, whether such clusters should be defined in terms of task membership or in terms of structural relatedness within the system.

S-R COMPATIBILITY. Location (or relocation) of any display on a multi-element panel should consider the spatial relation to the control element that drives (or should be moved in response to) that display's behavior. This consideration defines the force of stimulus response compatibility, which may conveniently be broken down into two subforces related to Collocation and Congruence (Andre, Haskell & Wickens, 1991; Andre & Wickens, 1991; Wickens, 1992). Collocation is simply an attractor force that pulls a display and its associated control together. Like the between-display attractors discussed above, such a force may be measured either in metric or object distance, and can be weighted by the importance (frequency of use) of the control-display pair in question.

It may not always be possible to adhere to collocation (consider, for example, the controls for a head up display, to be used by a pilot who cannot move the hands far because of high G forces). The principle of congruence, applicable here, dictates that the spatial ordering (e.g., left-right, top-bottom) of a set of displays should be congruent with the ordering of the corresponding control set. We say that the set may be either congruent (Figure 11a), acongruent (Figure 11b), or incongruent (Figure 11c) with, of course, any continuous angle in between. How might such a "force" be quantified? We have argued (Andre & Wickens, 1991) that the cosine of the angle between the two arrays nicely expresses this congruence. This formula has two nice properties: first, it clearly runs from maximum positive (congruence) to 0 (acongruence) to maximum negative (incongruence). Second, if one member of a parallel congruent array pair (Figure 11a) is rotated away from parallel, it

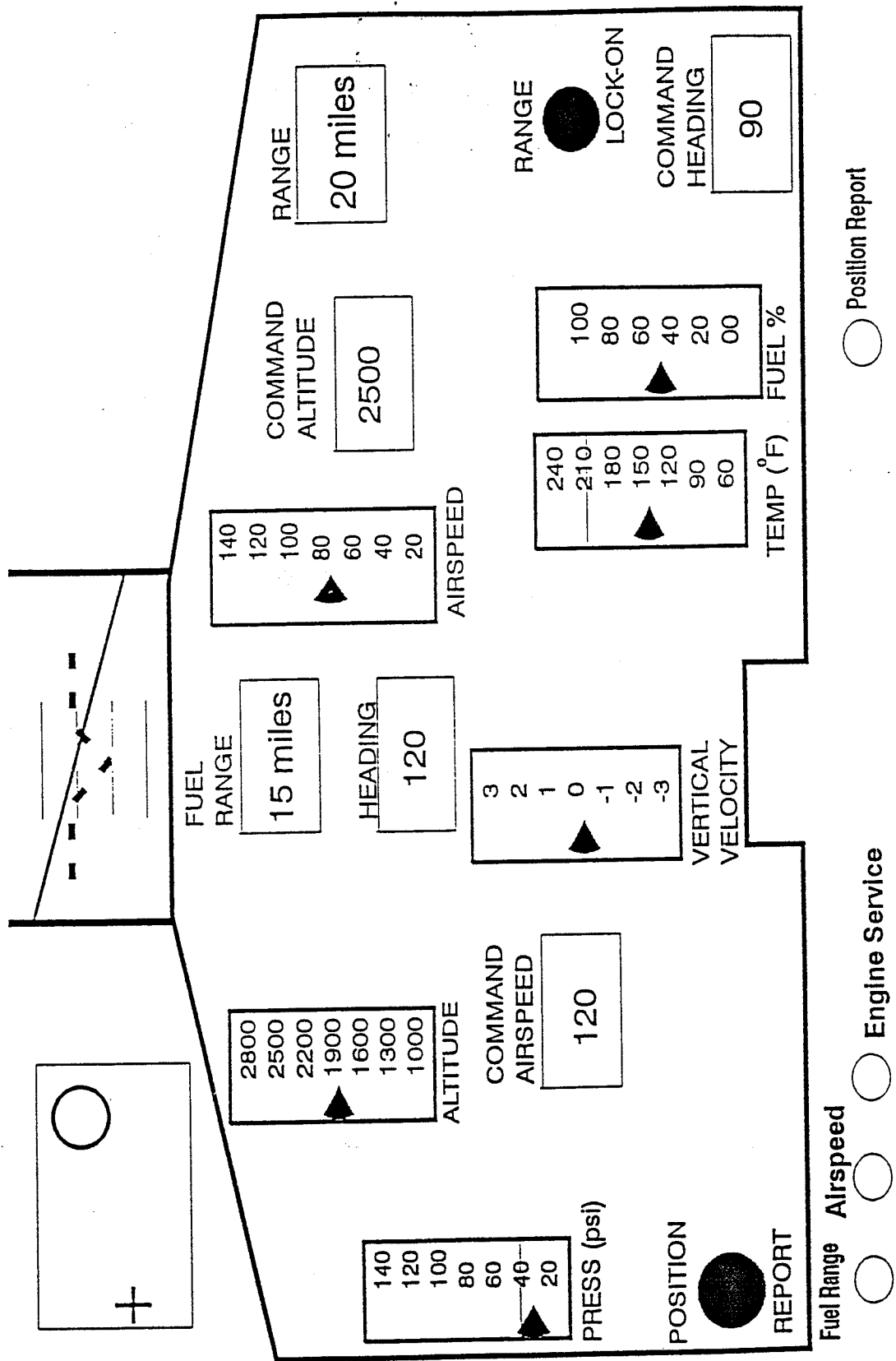


Figure 10. Condition 3 display panel depicting experimenter-defined low grouping and high priority.

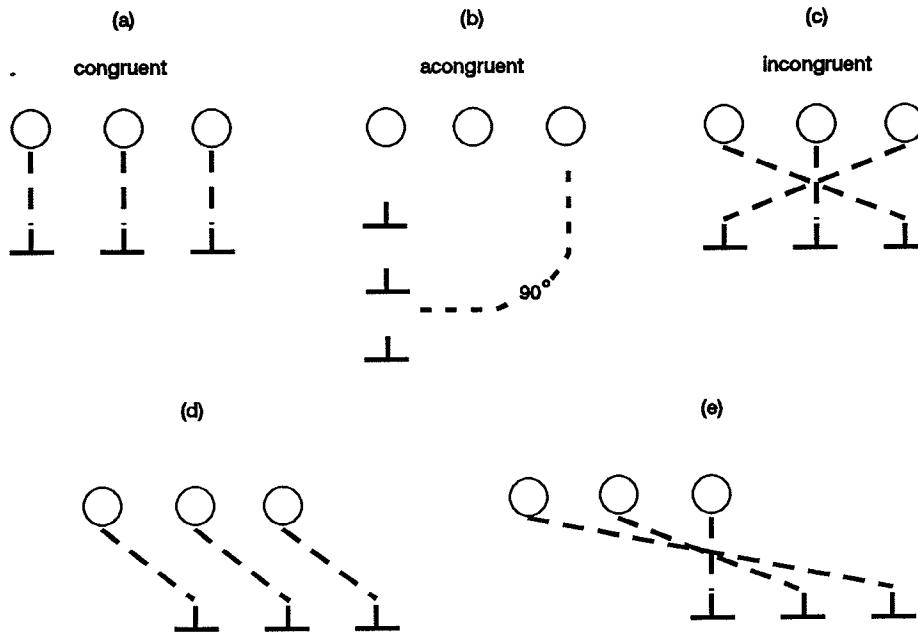


FIGURE 11: DIFFERENT COMPATIBILITY MAPPINGS BETWEEN THREE DISPLAYS AND THREE CONTROLS.

TABLE 2
DISPLAY LAYOUT MODEL FACTORS

FACTORS	CHALLENGES
1. Importance	Frequency or criticality?
2. Information Access Effort	Peripheral resolution with objects--size, motion, color. Head-field angle.
3. Search Uncertainty	Definition of "objects" inducing clutter. Spatial frequency analysis?
4. Confusion	
5. Relatedness	Task or structure? Quantification issues.
6. S-R Compatibility	Colocation versus congruence? Dedicated versus reach control? Defining array membership.

does begin to impose heavy penalties until the angle is near 90° (Figure 11b). This prediction is consistent with recent data we have collected, suggesting that 45° alignments produce no cost to performance relative to parallel alignments (Andre, Haskell & Wickens, 1991). That is, as long as the left-right (or top-down) ordering of the two arrays may be correctly matched, the cognitive links between controls and displays remain relatively automatic. The cosine formula nicely adheres to this characteristic.

We have at least some evidence that the relative strength of congruence may be greater than that of collocation. When the two are placed in conflict with each other, as in Figures 11d and 11e, performance appears to be better in configuration d, conforming to congruence but violating collocation, than in the opposite mapping (e) (Andre et al., 1991). The strength of S-R compatibility relative to the functional and priority display grouping principle discussed earlier was also evaluated in Andre's dissertation (Andre & Wickens, 1991). Here, each display combination was replicated with two different mappings of a display "array" (a pair or triad) to an associated control array, a congruent and an incongruent one. It turned out that performance differences between these two mappings were relatively small, compared to be performance differences created by manipulating the display grouping factors. This finding is of potential importance, and illustrates one of the things that computational models can tell us; not that it is OK to violate S-R compatibility in design, but when a trade-off must be made that adheres to display grouping but violates compatibility or the converse, the former will provide the better design.

Table 2 presents a summary of the factors identified to influence display layout, and the quantification challenges they present. In closing, let me emphasize that one other parallel effort which also appears to be making progress toward the goal of display layout quantification. This is Lohse's UCIE--a computer program which examines the efficiency of graphical formats for different tasks and graphical interpretations (Lohse, 1991). Based heavily upon the search and scan strategies of operators as they retrieve different pieces of information from the graph, UCIE also draws upon the time and capacity estimates of different mental operations, carefully tabulated by Card, Moran & Newell (1986). This model has received some encouraging initial validation. While the domains of graph interpretation and of multi-element display panel processing are quite different (the latter is dynamic, typically more complex, and must support a wide variety of tasks), there are clearly several important issues in computational modeling that can be shared between the two.

CONCLUSION

The quantification provided by valid computational models of display layout and multitask performance can accomplish three important goals: (1) The display layout models can allow designers to choose between alternative formats when constraints prevent all design principles from being satisfied and the designers must "trade-off" adherence to one principle against violation of another. (2) The numerical output of such models provides an overall "figure of merit" which can be used to optimize the layout of a given display panel (or the sequencing requirements of a set of tasks). (3) To reiterate the point made at the outset, the valid numbers provide ammunition for the human factors engineer to lobby for inclusion of their considerations in design. While the host of factors and their interactions which should ultimately be incorporated in a full-blown computational model sometimes seems overwhelming, it may be, as is often the case in psychology, that a few well-chosen and carefully but simply implemented components can predict a substantial amount of variance in human performance. That would be a great step forward.

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