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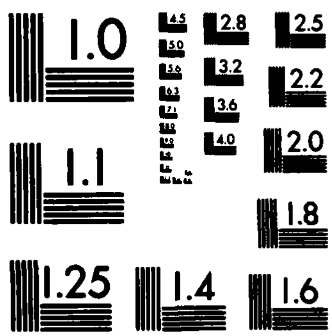

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The Limits of Multiple Resource Theory: The Role of Task Correlation/Integration in Optimal Display Formatting

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This report presents a theory of the optimal display format for tasks that have multiple stimulus elements. Our previous research indicates that these various elements should be presented to display channels that employ separate resources (e.g., be distributed between auditory and visual modalities). In this report we suggest that this distribution should not be done to the extent that (a) the values of the various display elements are correlated (e.g., temperature and pressure of gas in a pipe), (b) the

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Abstract

This report presents a theory of the optimal display format for tasks that have multiple stimulus elements. Our previous research indicates that these various elements should be presented to display channels that employ separate resources (e.g., be distributed between auditory and visual modalities). In this report we suggest that this distribution should not be done to the extent that (a) the values of the various display elements are correlated (e.g., temperature and pressure of gas in a pipe), (b) the separate elements must be integrated into a single mental model of the environment. Collectively, we define these two conditions as the degree of correlation/integration. As correlation/ integration increases, the relative advantages of separate resources decreases. The research in our own and other laboratories that supports this concept is reviewed.

The Limits of Multiple Resource Theory: The Role of Task Correlation/Integration in Optimal Display Formatting

Christopher D. Wickens & David B. Boles

The purpose of this report is to describe a theoretical framework for predicting the limits of application of multiple resource theory to dual task performance. In brief, this theory proposes that two tasks will be time-shared less efficiently if they impose demands on the common processing resources shown in Figure 1 (Wickens, in press, 1984). The particular theoretical framework is meant to resolve some seeming contradictions that exist in the experimental data relating task similarity to dual task time-sharing efficiency. On the one hand, we have demonstrated in several experiments that the more similar two tasks are, in terms of their competition for processing resources (i.e., input and output modalities, central processing codes), in the multiple resources model, the greater will be the degree of task interference (e.g., Wickens, Sandry, & Vidulich, 1983; Vidulich & Wickens, 1982). On the other hand, there are a more diverse set of results coming from a variety of sources that suggest the opposite conclusion: Time-sharing efficiency improves with greater similarity between tasks and task elements. In the following pages we shall describe these different classes of results, and then attempt to integrate the two contradictory classes of results within the framework of a testable theory.

1. Attention switching. LaBerge, VanGelder, and Yellott (1971) compared the time it took to switch attention to unexpected stimuli that were presented along the auditory or visual modality. The stimuli were lights or tones that required a left or right keypress response. Attention was aligned to an expected sensory channel by a probablistic

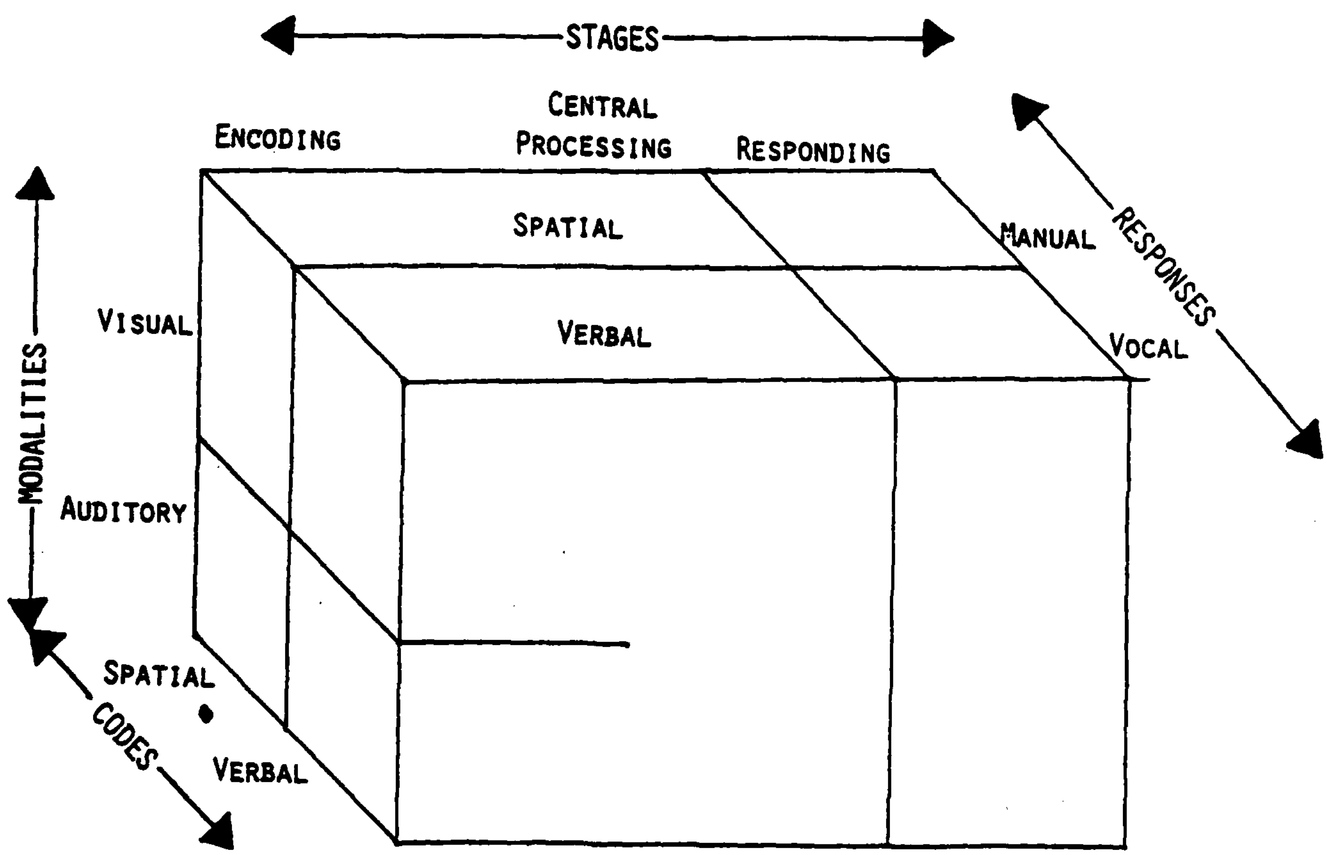

Figure 1. The proposed structure of processing resources (after Wickens, 1983).

cueing technique, and the experimenters examined the delay in RT that resulted when a stimulus occurred on a non-attended channel (i.e., in the stimulus modality that was not expected on a particular trial). LaBerge et al. found an approximate 100 msec increase when attention needed to be switched between modalities, in contrast with conditions when attention could be maintained within a modality. In these results there is a cost to cross-modality stimulation that appears to run contrary to the view of multiple resource theory which predicts that cross-modal time-sharing will be uperior to intra-modal.

These results have been echoed to some extent by other research in our laboratory, where the advantages of employing separate input modalities have not always been terribly robust (i.e., Vidulich & Wickens, 1982), and have sometimes been absent altogether (Tsang, 1983; Wickens, Kramer, Vanasse, & Donchin, 1983). In fact, in the investigation by Wickens, Kramer, Vanasse, and Donchin, in which subjects performed a tracking task concurrently with an evoked potential-eliciting task requiring the discrimination of stimuli, there was actually an advantage to the intra-modal condition, in which visual tracking was time-shared with a visual probe task. In a related line of research Klapp (personal communications) has reported that monitoring of two asynchronous rhythms is easier if both are presented to the auditory modality than if one is auditory and one is visual.

2. Integral and separable dimensions. A series of empirical studies and theoretical analyses carried out by Garner (1970; Garner & Fefoldy, 1970) have drawn the distinction between pairs of dimensions that are said to be integral and those that are separable. While the clarity of this distinction has been challenged recently (e.g., Dykes, 1979; Smith & Baron, 1981), the original view proposed that integral

dimensions were those in which the level along one dimension could not be specified without specifying the other dimension. As an example, the height and width of a rectangle are said to be integral because it is impossible to specify the height of a rectangular stimulus without also specifying its width (Dunn, 1983). If the physical stimulus did not have width, it would not be a rectangle.

In one of Garner's paradigms (Garner & Fefoldy, 1970), integral dimensions are shown to provide efficient parallel perceptual processing. This processing leads to advantages when the dimensions are correlated, each calling for the same response, but to disadvantages when the dimensions call for different actions (see Hintzman et al., 1975).

Kahneman and his colleagues have expanded upon this treatment by arguing that the different dimensions of an object (which generally tend to be "integral" by Garner's criterion), all "want" to be processed in parallel (Kahneman & Chajczyk, 1983; Kahneman & Treisman, 1984). These investigators provide data indicating the extent to which different dimensions of an object (color and shape) facilitate each other's processing in a cooperative fashion. An experiment by Lappin (1967) is also highly consistent with these results. Lappin reports that the color, size and shape of a single object can be efficiently processed in a single tachistoscopic exposure of the stimulus. But subjects have a far more difficult time reporting the color of one object, the size of another and the shape of a third. The "objectness" in the first case fosters the parallel processing of its elements. Kahneman's recent research has established that the advantages to dimensional perception in a single object are not simply the result of the smaller visual angle, and therefore better stimulus quality relative to the control conditions with which it is compared. It is the "objectness" and not the extent of visual space that makes the difference.

These data are relevant to our general discussion because they suggest that the single dimensions of an object, dimensions which are thereby spatially and psychologically "closer" or more "proximate" than dimensions of separate objects, are better processed in parallel, and therefore lead to more efficient time-sharing. It is, of course, true that this proximity is not necessarily defined in terms of the multiple resource space. For example, we can assume that the dimensions of either one or three objects in Lappin's experiment are all processed by the visual-spatial resource. Nevertheless, this second category of results shares with the first, the property that time-sharing is found to increase with increased proximity.

3. Manual control research. A number of studies of dual axis tracking have reached conclusions similar to those reported above: that when two tracking tasks must be carried out concurrently, performance of both will be better if they are combined into a single integrated error indicator moving simultaneously in the X and Y axes, than if they are represented as two separate indicators (see Wickens, in press, 1983 for a summary). In fact, Navon, Gopher, Chillag, and Spitz (1982) have called attention to the fact that time-sharing can be nearly perfect under such circumstances. This phenomenon represents an example of extremely good parallel processing of two dimensions of a single stimulus.

These research findings in manual control have been extended to provide yet another example of a situation when time-sharing efficiency increases with increased proximity. This extention is the observation made by Chernikoff, Duey, and Taylor (1960), that dual axis tracking will be improved when two axes have the same rather than different dynamics. This superiority will hold even when the "different" condition sharing axes with a higher and lower order is compared with a "same" condition in which two tasks with higher order are time-shared (i.e., dual axis tracking is better with two second order control tasks than it is with a second order task time-shared with one of zero order). Presumably it is easier for the subject to time-share two independent axes, when only a single "internal model," or transfer function, need be activated in working memory.

A subsequent investigation by Chernikoff and Lemay (1963) integrated this finding with the observation of superiority of the single tracking display reported by Navon et al. (1982). Chernikoff and Lemay found that the *cost* of having dissimilar dynamics on two axes was reduced if the displays were also separate, but was enhanced if the displays were integrated into a single indicator. Stated in other terms, the *advantage* of an integrated display was reduced when the dynamics were different. Hence, these findings define a sort of "compatibility of similarity." Similar dynamics are most compatible when they are paired with similar (integrated) displays.

What, if anything, is the common theme that runs through these findings, beyond the general conclusion that more similar task or similar display elements *can* under some circumstances lead to increased time-sharing efficiency? A major component appears to be related to the similarity or integrality of task components. Thus in Garner's research, when both task elements called for a common internal response (i.e., there was redundant coding of two stimulus dimensions), then there was an advantage to integral (close) dimensions. In the manual control research, when the two axes called for a common integrated mode of internal processing--that is, their dynamics were identical--time-sharing improved, and favored an integrated display configuration.

The theory that we propose below asserts at its most general level that the advantage to display proximity of two tasks will be increased as the correlation/integration of task elements is increased. This very general statement needs elaboration of each of the underlined terms: 1) Display proximity refers both to similarity of display elements within the resource space and to similarity of elements within a given resource. Thus, proximity may refer to two visual configurations, as opposed to an auditory-visual (bimodal) one; or it may refer to two spatial configurations, as opposed to a spatial and a verbal one. Both of these cases refer to "between-resource" similarity. Alternatively, spatial proximity may refer to two spatial dimensions of a single object as opposed to two dimensions of two objects (within-resources similarity). 2) The correlation/integration (CI) of task elements defines two different concepts: (a) External correlation refers to the correlation of stimulus values. Thus, the pressure and temperature of a thermal process represent examples of externally correlated variables, since high values of one typically accompany high values of the other. So too do the aileron position and bank angle of an aircraft or, in a different domain, the years-in-service and pay-grade of Naval personnel. (b) Internal correlation or integration refers to the extent to which changes in two external stimuli (whether these are correlated or not), must be combined together in a single internal model, before action can be selected.

The air traffic control task offers a good example of integration. Although the flight courses of the various aircraft on a given display may be uncorrelated with each other (low external correlation), the controller obviously needs to integrate the movement of the various aircraft together into a single internal model of the air space before recommending an action to any one aircraft. Another example is provided by the many attributes that must go into a decision of whether or not a unit commander should deploy a particular force. Here again the attributes or cue values may be unrelated to or uncorrelated with each other (e.g., readiness status of the units, weather patterns, intelligence reports). However, the decision clearly requires integration of this material. According to the theory of task integration, the air traffic control problem would be a situation ideally tuned for display proximity, because the integration is high. Indeed it makes a great amount of intuitive sense to present aircraft all within one display format (visual-spatial), rather than to present half of the craft in one format, and half in the other--or to present latitude spatially and longitude in terms of numerical coordinates.

At the other extreme, consider a situation in which integration is not present. Consider, for example, control of "inner loop" flight control variables and a reading of weather patterns in an aircraft. Information for these two tasks will best be displayed with low proximity. There is little integration required of these two sources since they essentially form two separate tasks rather than two display elements of a single task. The two will thus benefit from a display using separate resources.

The general theory we propose is represented in Figure 2a. The ordinate is some measure of general task performance or time-sharing efficiency (the specific measure will be seen to depend upon the abscissa value). The abscissa describes the degree of correlation/integration. This may be zero--in which case the subject is performing two independent tasks--the kind of time-sharing research most often investigated in our laboratory--or it may range to near "unity." An example of a unity correlation task would be two tracking tasks with identical input functions. An example of a unity integration task would be one in which two digits (the task elements) must be added to produce a single output. Of course, correlation and integration are two functionally independent concepts. Hence, technically the abscissa should be two axes and not collapsed into a single one. Since the theory predicts that both correlation and integration will have the same impact on performance efficiency and proximity, however, for the moment we chose to combine the dimensions. Their separate effects will be considered below.

The two curves on the graph in Figure 2a describe endpoints on a continuum of "display proximity." The "close" label may refer to two dimensions of a single object. The "distant" label might refer to information conveyed by the height of a bargraph and the verbal content of an auditory (spoken) message. The difference in slopes of the two curves--the interaction between the two independent variables--is the fundamental property of the proposed theory.

We predict that as task elements show greater correlation/integration, they will be progressively better served by display configurations that are proximate. The particular representation in Figure 2a shows a crossover interaction. That is, greater distance will be better at low levels of C/I and worse at high levels. This figure also shows a main effect of C/I suggesting that tasks in general will be easier if their display elements are correlated (this has been demonstrated in decision-making research, Phelps & Shanteau, 1978; Medin, Alton, Edelson, & Freko, 1982) and/or if they allow some integration of their elements into a single mental model--therefore creating more of a single task configuration. It is important however, to realize that the theory does not necessarily predict the specific form shown in Figure 2a. The forms shown in Figures 2b, c, & d are also consistent with the basic tenants, all of which show that increasing C/I will increase the relative merits of close versus distant configurations, whatever the absolute merits of each configuration may be.

As we have noted, most of the research in our laboratory has taken place at the far left region of Figure 2, and hence has been consistent with multiple- resource theory predictions of superior performance (time-sharing) efficiency when there is greater distance between display formats. However we, like Chernikoff, Duey, and Taylor (1960) have also found that there is improved performance with greater task integration in a manual control task, when both tasks use the same dynamics (Wickens & Tsang, 1979). A recent investigation by Scott and Wickens (1983) examined a point closer to the right of the continuum, using an information integration/decision task in which the reliability and diagnosticity of a sequence of information cues needed to be combined in order for subjects to formulate a judgment of the likelihood that one hypothesis or the other was in effect. We concluded that performance when these dimensions were expressed as an integrated object was better than when expressed as separated numerical values, a finding consistent with the positioning of the right hand part of the two curves in Figures 2a, c, and d. What we have not done is to systematically vary, within an experiment the display and task

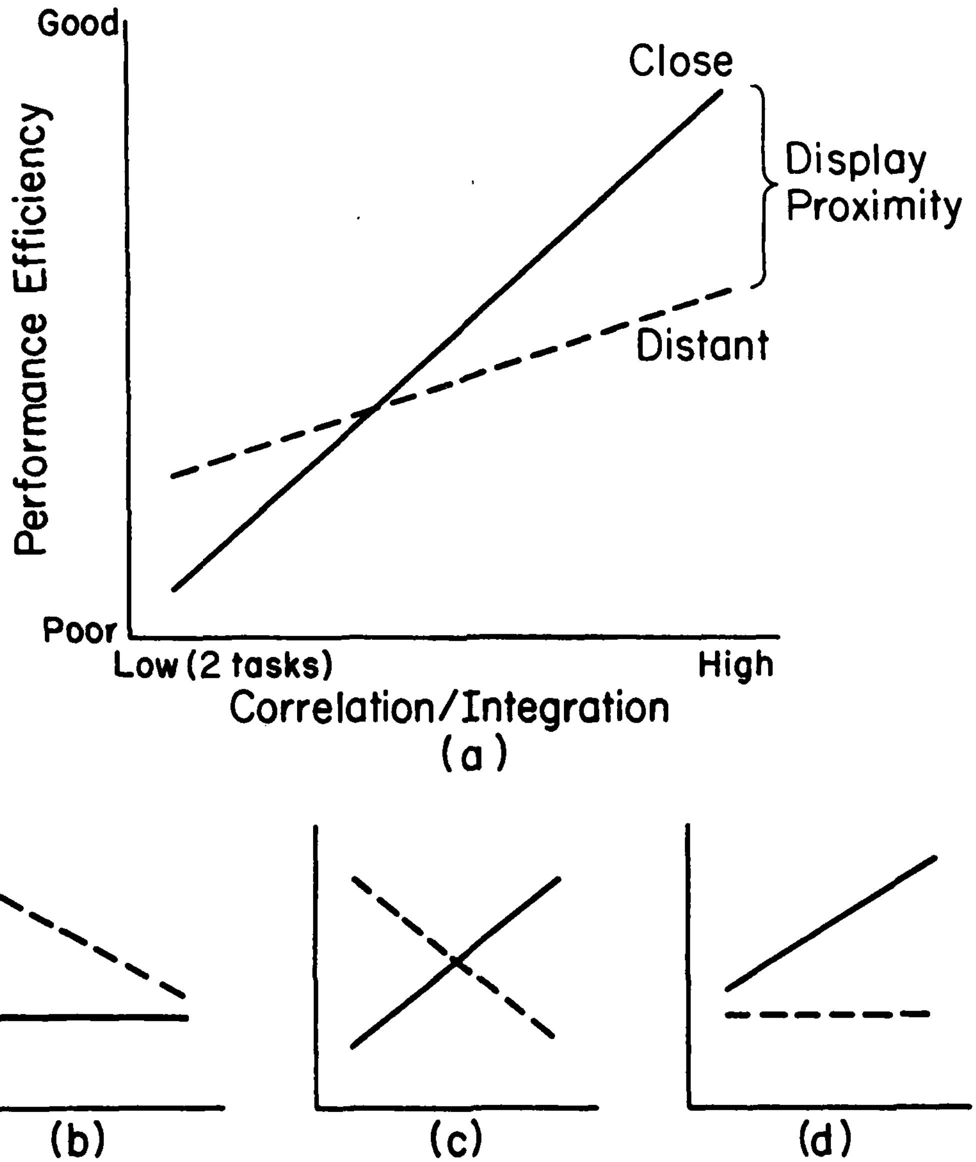

Figure 2: Predicted effect of correlation/integration and display proximity on performance efficiency. a), b), c) and d) show different forms of the predicted interaction.

correlation/integration properties to assess the nteraction shown in Figure 2. An accompanying report (Boles & Wickens, 1983) partially accomplishes this purpose by determining if the interaction holds across different sorts of integration variations, and different manipulations of display proximity.

In more general terms, we anticipate that three general applied guidelines could potentially flow from our research: (a) When should spatial analog data be mixed with verbal numerical data, and when should data of entirely one format be employed? (b) When should "holistic" object displays like the iconic display of nuclear reactor safety parameters (Wood, Wise, & Hanes, 1981) be employed? (c) What are the limits/constraints on the use of voice display? Voice display in a visual environment is an example of "distant" proximity. Hence, when the C/I is high, voice display may not be an effective means of presenting information. The three technical reports to follow will address each of these issues.

It is certainly true that there are ways in which the present theory should be elaborated. For example, we have described the C/I dimension as unitary, whereas clearly stimulus correlation and task integration may each be varied independently of each other. Thus, rightfully Figure 2 should be elaborated to the three dimensional portrayal of Figure 3, thereby increasing the complexity somewhat. In this regard the tracking studies described above provide data that supports the interaction of proximity with <u>integration</u> while Garner's work on integral and separable dimensions with correlated and uncorrelated stimuli provides data that supports the interaction with correlation. Furthermore, to make matters still more complex, the stimulus correlation dimension may itself be described in terms of

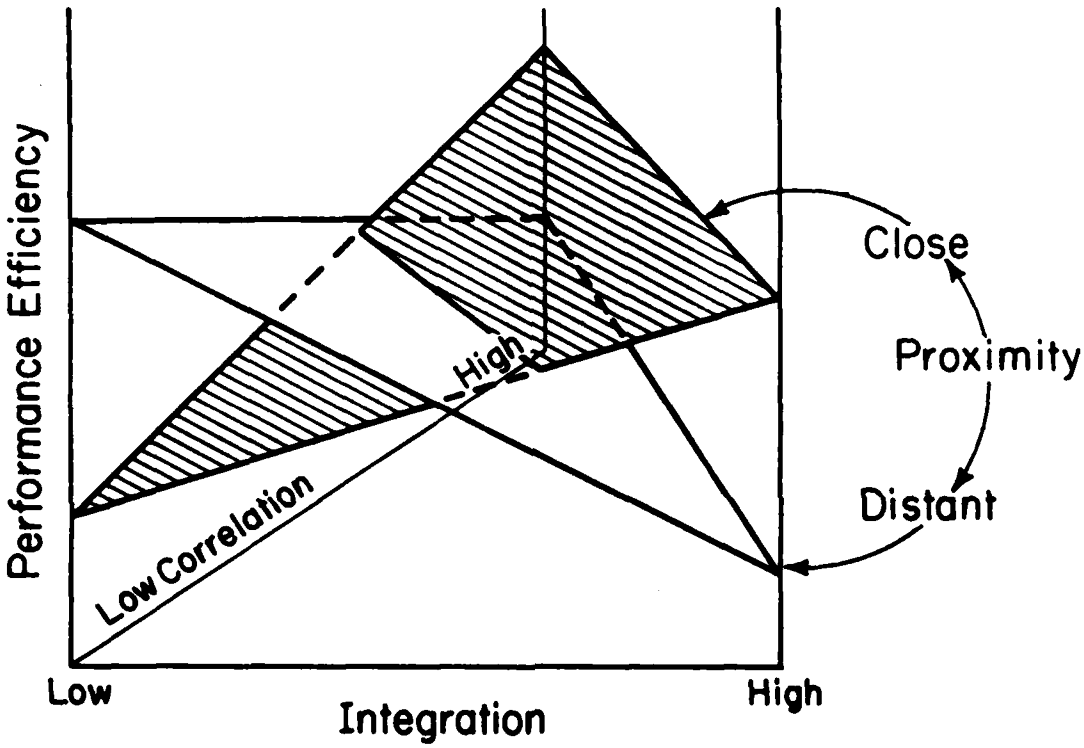

Figure 3: Predicted effects of correlation and integration on performance efficiency.

whether the correlation is 0-lag, or is time-lagged to varying degrees (e.g., the lag between aileron position and bank angle in aviation). It would appear that increasing time-lag would serve to reduce the perceived correlation and therefore shift a task toward the low end of the C/I curve.

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