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The Proximity Compatibility Principle: Its Psychological Foundation and Relevance to Display Design

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In this report we describe the concept of the proximity compatibility principle (PCP) and demonstrate its relevance to display design: Displays relevant to a common task or mental operation (close task or mental proximity) should be rendered close together in perceptual space (close display proximity). Different forms of task proximity are discussed, as are the different information-processing mechanisms that underlie the effects of the several different design manipulations of display proximity. Experimental data that support this process-based elaboration of PCP are then reviewed in design contexts relating to aviation, graphs, display layout, and decision aiding.

INTRODUCTION

Consider the task confronting the designer of an interface for a complex system. Multiple sources of information are provided by the system, and task analysis, coupled perhaps with visual scanning analysis of operators using a prototype, has provided some insight regarding the nature of the operator's information needs: which sets of indicators need to be compared or combined (used simultaneously), which are to be used in sequence to perform a certain task, which may rarely be used in sequence but still pertain to common system elements, and which have nothing to do with one another.

This article addresses the issue of where these different sources should be placed with respect to one another and how they should be organized. With an earlier generation of electromechanical indicators, the issue was simply one of spatial location on a two-dimensional (2D) display panel. However, the greater flexibility of electronic display options enabling display integration, color, and multifunctionality increases the flexibility of design and leads to a far more complex meaning assigned to the concept of "where."

We describe the *proximity compatibility principle* as one guideline to use in determining where a display should be located, given its relatedness to other displays. The PCP depends critically on two dimensions of proximity or similarity: perceptual proximity and processing proximity. *Perceptual proximity* (display proximity) defines how close together two display channels conveying task-related information lie in the user's multidimensional perceptual space (i.e., how similar they are). Thus two sources will be perceptually more similar (in closer proximity) if they are close together, share the same color, use the same physical dimensions

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(e.g., both use orientation or length), or use the same code (e.g., both are digital or both are analog). For the designer, perceptual proximity is influenced by variation in where and how information sources are displayed, so this may be also referred to as *display proximity*.

Mental or *processing proximity* defines the extent to which the two or more sources are used as part of the same task. If these sources must be integrated, they have close processing proximity. If they should be processed independently, their processing proximity is low. The principle proposes a compatibility between these two dimensions. If there is close processing proximity, then close perceptual proximity is advised; conversely, if independent processing is required, distant perceptual proximity is prescribed.

Certain aspects of the PCP are familiar to the design community. For example, the classic principle of functional grouping dictates close proximity between functionally related instruments (Bailey, 1989; Bonney and Williams, 1977) and has been successfully practiced in the layout of aircraft instruments. However, we go beyond this principle in three respects. First, as noted, we broaden the concept of 2D space to include concepts of perceptual space and perceptual "closeness" or similarity (Garner, 1970, 1974). Second, we consider not only the benefits of closeness but also its costs. Third, we attempt to relate the principle to a number of different psychological or information-processing mechanisms that are responsible for the PCP effect. Because of the multiplicity of psychological mechanisms involved, we emphasize that the PCP is not a theory but, rather, is based on a set of theoretical principles of human information processing that bear on the "where" aspect of the display designer's task. Finally, we believe that the PCP is complementary to recent principles of ecological interface design (Bennett and Flach, 1992; Bennett, Toms, and Woods, 1993; Rasmussen and Vicente, 1989; Vicente and Rasmussen, 1990, 1992), not in competition with them, and we hope to show how these ecological principles are integrally related to at least one of the mechanisms underlying the PCP.

Given that the display-task interaction characterized by the PCP is the result of the combined action of several different psychological mechanisms, it is not surprising that this interaction may take on several different display forms, depending on which mechanisms are dominant in evaluation. As shown in the bottom panels (b through e) of Figure 1, any form could be observed as long as the following verbal description is preserved: "The benefit of closer display proximity is increased, or its cost is decreased, as the task integration requirements are increased." In the first part of this paper, we describe the variables and psychological mechanisms that mediate the form of this interaction. Then we examine these mechanisms as they are reflected in four domains of display application.

RELEVANCE TO DISPLAY DESIGN

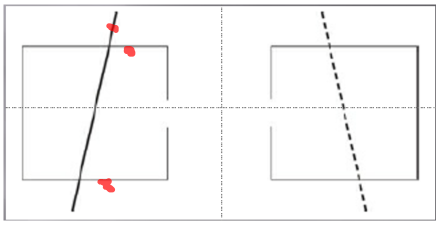
In this section we consider the three key features of the PCP: the characteristics of task proximity and of display proximity and the posited psychological mechanisms that mediate the relation between them.

Task Proximity

Task proximity may be defined by several features, or along several dimensions. To some degree these may be ordered along a continuum ranging from *close* to *independence* with three major hierarchical categories, each containing a number of subordinate categories.

A. Integrative processing (high task proximity). Within this category are computational and Boolean integration. *Computational integration* involves integrating or combining two pieces of information through an arithmetic operation, as when the pilot must compare command with actual altitude (subtraction), or when the industrial monitor must multiply the rate of production of a machine by the duration of its computational operation to assess the amount produced. We refer to this as *integration proximity*.

Boolean integration is required when two pieces of information must meet some conditions of Boolean logic for a given action to be



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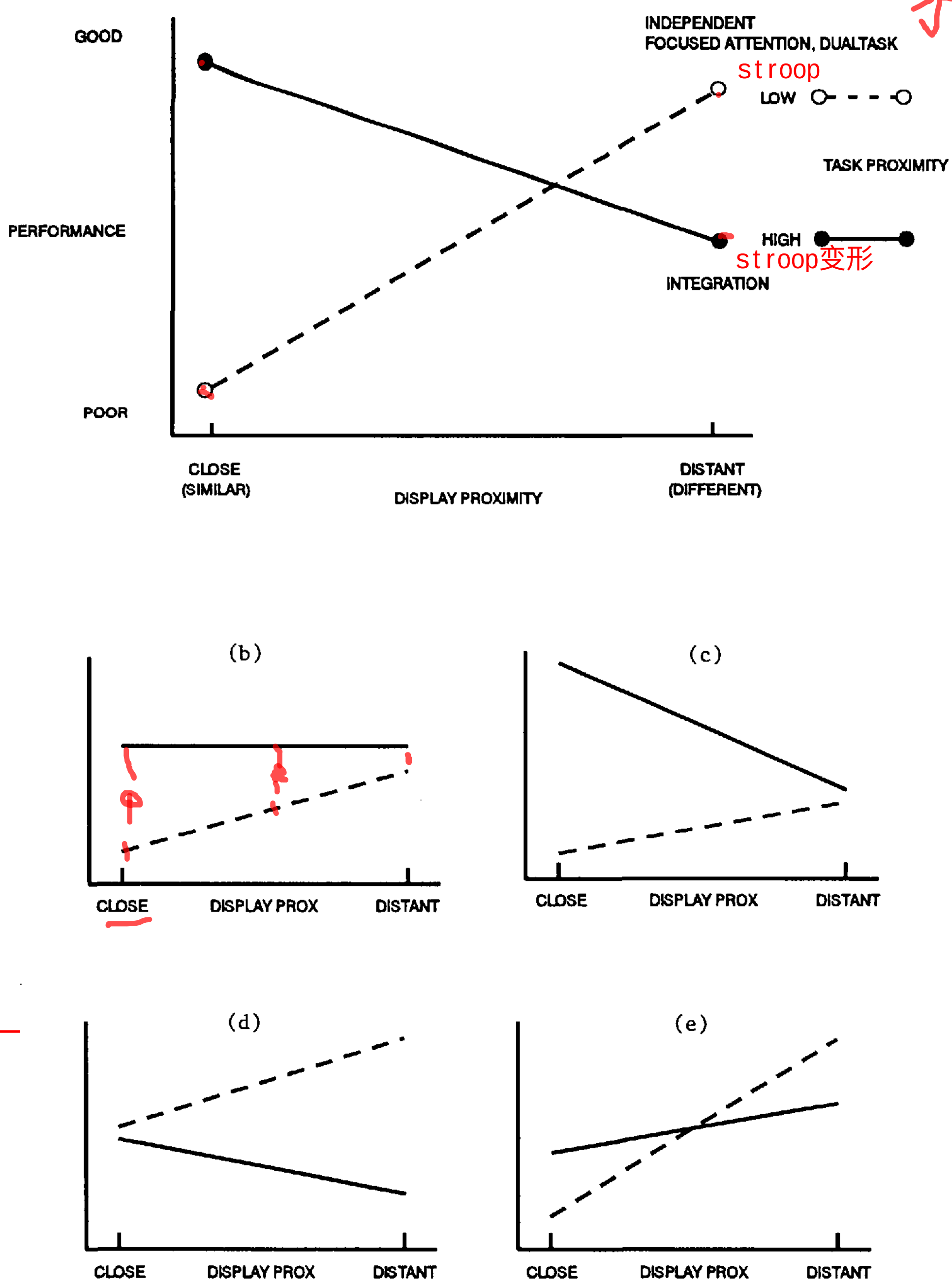


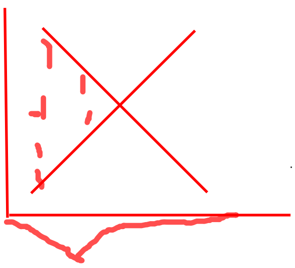


Figure 1. *Top: The proximity compatibility principle. Bottom panels show various forms that the interaction predicted by the PCP may take. Adapted from Wickens and Boles (1983).*

taken. For example, to proceed with an aircraft landing approach, airspeed and altitude must be within certain parameters at the same time, even though, unlike computational integration proximity, they cannot be directly compared or computationally "integrated" because their variables may be expressed in qualitatively different units. Coury and his colleagues (e.g., Coury and Boulette, 1992; Coury, Boulette, and Smith, 1989) have employed Boolean integration in their examination of object displays by asking subjects to classify four-dimensional stimuli into categories based on whether each of the values was within critical ranges.

Formally, both types of integration proximity may be defined as having a many-to-few mapping of information sources to responses (or internal cognitive states), a mapping that requires information condensation rather than filtering (Posner and Mitchell, 1967). Both forms would also dictate a high score on a sequence of use criterion.

B. Nonintegrative processing of similar tasks (lower proximity). Different information sources may share some other features of similarity instead of (or in addition to) their need for combination. Five examples of such similarity are provided in the following paragraphs. These are not mutually exclusive, and a given set of sources may share any or all of them.

Metric similarity describes sources that portray information in the same units or metrics. Two displays of gas pressure share metric similarity, but one of gas pressure and one of temperature or flow rate do not.

Statistical or *covariance similarity* describes the extent to which values covary over time. This may arise because of a common source of input to both displays, or because the operator's input to one may perturb the output of another. An example is the pitch and bank indicators of an aircraft. In one sense, these are two independent axes of flight control, but a change in bank will affect pitch, so that over time the changes in these variables will be correlated.

Functional similarity refers to the similarity of the units or objects being measured, as represented in the operator's semantic space (i.e., the knowledge base built from experience with the system). For example, all indicators representing features of a given system component (e.g., a particular turbine) would be said to define high functional similarity. So would all indicators of a given class of information (e.g., all warning indicators). Functional similarity could be derived from multidimensional scaling techniques eliciting the structure of the operator's semantic space or mental model of the displayed system (Hanisch, Kramer, and Hulin, 1991; Roske-Hofstrand and Paap, 1986). As such, however, the final solution would probably reflect the combination of other features of similarity.

Processing similarity defines similar information-processing or computational routines that are to be performed on two or more data sources. Two tracking tasks will have greater processing similarity if they share identical dynamics (e.g., velocity control) than if they do not (Chernikoff and LeMay, 1963; Fracker and Wickens, 1989).

In *temporal proximity*, two tasks typically may be performed in the same time frame to meet the same overall goal, but they may use very different processing mechanisms, be uncorrelated, and have no influence on each other's variables. For example, keeping the car in the center lane and checking the map to see where you are going are both part of the driving task; hence, you must make frequent visual scanning transitions between the information sources. Although the two tasks bear little similarity in their processing mechanisms, they share the same higher-level goal and so can be related if the concept of "task" is considered at a fairly coarse "grain size" (Andre and Wickens, 1991). In the absence of any other similarity metric, the degree of temporal proximity between two sources should be predictable from the product of the independent assessment of the frequency of use of each source alone.

C. Nonintegrative processing of dissimilar sources (independent processing). This lowest (most distant) level of task proximity results when there is no interaction or similarity between the information sources or the processing mechanisms involved in the two tasks. This describes independent processing. Although the two tasks may be performed concurrently in the dual-task paradigm (e.g., conversing while driving), this level also describes situations in which they may be performed in sequence, or in which one task is not performed at all, such that information from one source of task-related information must be filtered as attention is focused on the other single task. This latter instance, defining the focused attention task, has played a prominent role in experiments on the PCP.

The distinctions among these many forms and levels of task proximity add complexity to the PCP. For example, data collected by Carswell (1990, 1992) suggest that computational and Boolean integration proximity tasks may benefit from different forms of display proximity. Note also that the two categories of task proximity—integrative requirements and task similarity—are, in a sense, independent of each other. That is, either integrative or nonintegrative tasks could share different features of similarity between their tasks.

Manipulations of Display Proximity and Their Psychological Mechanisms

In this section we list several things that can be done to the *physical* rendering of two or more displayed information sources in order to create a so-called psychological closeness, or perceptual similarity, between them. Many of these manipulations have been inspired by the Gestalt laws of perceptual organization, including the laws of proximity, similarity, area, closure, and good continuation (see Pomerantz and Kubovy, 1986, for a detailed discussion of the Gestalt thesis). Others derive from Garner's distinction among integral, separable, and configurable dimensions (Garner, 1974). Figure 2 provides examples of six manipulations that we believe can be used to increase (or decrease) display proximity.

First, and perhaps most obvious, display proximity can be increased by increasing the spatial proximity of the information channels. Second,

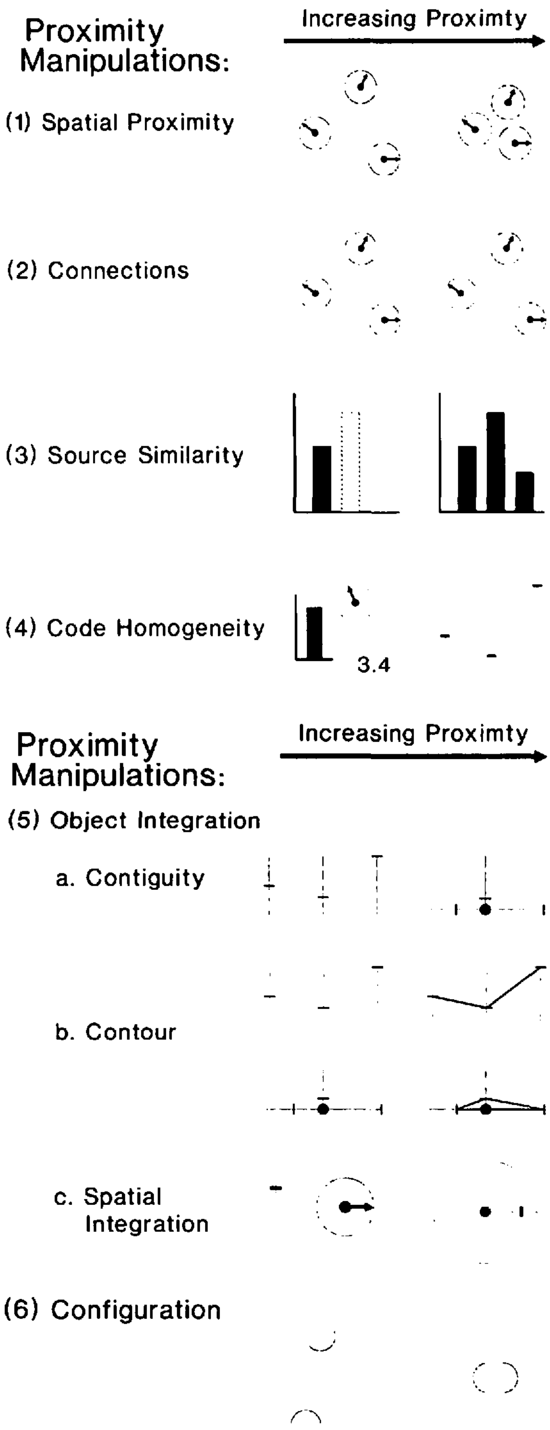


Figure 2. *Six different ways of manipulating the proximity or perceptual similarity of display elements.*

proximity can be increased by adding line segments that provide connections among or enclosures around information channels. Third, source similarity focuses on the way in which the various information codes are packaged, but it does not describe the code conveying the information itself. Source similarity might be implemented by making all information sources the same color, orienting them along the same axis, or showing each source in decorative perspective.

Fourth, one can match rather than mix the codes used to represent the information conveyed by several sources of quantitative information. Thus in a homogeneous code display, each variable is coded using the same analog property (e.g., length, orientation, or brightness) or by using all-digital formats. Alternatively, codes may be mixed; one source of information may be coded by variations in length, another by variations in position, and yet another by digital code. In distinguishing code homogeneity from source similarity, it should be emphasized that the latter refers to the manipulation of an aspect of the information source that may help a user identify what is being measured, but it is *not* the aspect of the display that represents the measurement itself (i.e., the change in the variable). Thus a feature of a bar chart, such as its color, may indicate that the bar represents temperature, whereas the height of the bar is the code for the actual temperature value.

A fifth manipulation of display proximity, *object integration*, has received much attention in the research literature (for reviews, see Bennett and Flach, 1992; Carswell, 1992; and Wickens, 1986). In general, this manipulation involves arranging information sources so that they appear to the user to be part of a single object. In practice, objectness has been created in a number of ways, some of which are illustrated in Figure 2, number 5. One method is to decrease the spatial proximity and arrangement of two or more information sources so that they are contiguous. A second method is to add contours to the display, sometimes forming a closed object with area. Note that the addition of contours to form an object is different from the simple connections of display channels illustrated in Figure 2, number 2. Connections (and enclosures) are assumed to be fixed elements of the display, whereas the contours added to create object displays actually change shape or location with variations in the values of the connected information sources. Object displays may also be created from extreme spatial integration so that the individual information sources are not in separate parts (or locations) of the display; for example, a single line segment that varies in length to represent one variable while varying in orientation or color to represent a second. A corresponding example might be a dot in an x,y plane (or a point in an x,y,z volume) rather than two (or three) parallel measures of extent. This special case can be called *dimensional integrality*.

It is important to note that these manipulations of object integration are somewhat dependent on the nature of the codes used to represent data values. Although contiguity may be used for virtually any combination of codes, the addition of contour is applicable to codes that vary in spatial position or extent, and spatial integration is restricted mostly to heterogeneous codes (e.g., variable color bar graphs).

The sixth manipulation of display proximity, *configuration*, refers to perceptual proximity created by a combination of homogeneous features, close spatial proximity, and the arrangement of sources to "configure" in a new pattern (Bennett and Flach, 1992; Pomerantz, 1981). In Figure 2, number 6, the parentheses pair on the right configure to form a closed object, whereas those on the left do not. As we discuss later, configural displays have many of the same characteristics attributed to object displays, but the two are quite distinct.

The extent to which any of the manipulations listed in Figure 2 actually represent display proximity can be assessed by psychophysical means (e.g., psychophysical rating scales; Burns and Shepp, 1988; Garner, 1970, 1974). This will avoid the circularity of operationally defining display proximity only in terms of its interaction with task proximity in performance. It should be noted also that many of the historical roots of the PCP, including the fundamental interaction between task and display proximity, may be found in Garner's work (1970, 1974; Garner and Felfoldy, 1970) on dimensional integrality and separability, as well as in the work of Eriksen and his contemporaries, who have explored the costs imposed by surrounding distractor elements when focusing attention on critical target elements (e.g., Eriksen and Eriksen, 1974; Eriksen and Yeh, 1985; Kramer and Jacobson, 1991; Kramer, Tham, and Yeh, 1991).

In the following discussion of display proximity, the work of these and other researchers will be discussed as it applies to the design issues addressed by the PCP. This discussion will be organized around the basic information-processing mechanisms that are assumed to underlie the effect of display proximity on performance in high-proximity (integration) versus low-proximity (independent and focused attention) tasks. In describing each mechanism, we will list those proximity manipulations most likely to produce the proposed performance outcomes.

Information Access Cost and Working Memory: Spatial Proximity, Feature Similarity, Connections and Enclosures

Suitable proximity manipulations include spatial proximity, source similarity, and connections and enclosures.

Closeness in space, commonality of color, and lines connecting or enclosing two sources will generally make their comparison and integration easier because of the decrease in visual search cost and time necessary to go from one to the other. This search effort depends not only on eye and head movements but also on the internal movement of attention (Van der Heijden, 1992). Elsewhere we have referred to this as *information access cost* (IAC), involving movement of attention, the eye, and the head (Wickens, 1992). The concept of IAC could extend as well to retrieving screens in a multifunction display (Seidler and Wickens, 1992, 1995) or retrieving information from a database. The physical contribution of eye and head movement to IAC on a dedicated display will be reduced by increasing spatial proximity. Two sources within a few degrees of visual angle, for example, can often be sampled in sequence without eye movements. However, the contributions to IAC of attention movement (whether or not coupled with eye movement) are also affected by factors related to visual clutter, the disruptive role of which in visual search is by now well established (Teichner and Mocharnuk, 1979; Treisman and Gelade, 1980). Thus the benefits of spatial proximity, common color, and connectedness will be enhanced when that search must take place in a "noisy" (cluttered) environment. The specific advantage of creating connections to reduce IAC may result from the automaticity with which mental curve or line tracing is carried out as a relatively primitive perceptual operation (Jolicoeur, Ullman, and Mackay, 1986; Pringle and Egeth, 1988) and has been associated with specific neurophysiological mechanisms disrupted by symptoms of Baintis syndrome (Rafal, in press).

In terms of the PCP, the reason that increases in IAC disrupt performance on integration tasks more than on independent tasks (Martin-Emerson and Wickens, 1992; Vincow and Wickens, 1993) is that integration tasks often impose an extra load on working memory, both to carry out computation required by the integration and to retain information for one source while the other source is accessed. Hence the resources required for these processes will compete with the greater resources required to search for more distant information to access (Liu and Wickens, 1992b). For example, Vincow and Wickens (1993) observed that the cost of separating two sources of tabular information into different display panels (greater IAC) was enhanced to the extent that complex mental operations of multiplication and division were required to integrate them (computation integration).

In the context of Figure 1, it is important to note that close proximity as discussed in this section will provide a great benefit to integration—or to any task that requires the sequential retrieval of two or more sources—but will generally produce no cost to focusing.

Emergent Features: Replacing Mental Computation with Perception

Suitable proximity manipulations include homogeneous codes, connections, spatial proximity, feature similarity, object integration, and configural displays.

Following on the work of Pomerantz and Garner (1973; Garner, 1978; Pomerantz, 1981; Pomerantz and Pristach, 1989), Sanderson, Flach, and their colleagues have highlighted the role of emergent perceptual features in fostering information integration (Bennett and Flach, 1992; Bennett, Toms, and Woods, 1993; Buttigieg and Sanderson, 1991; Sanderson, Flach, Buttigieg, and Casey, 1989). Emergent features are properties of the visual display other than the so-called raw codes the designer uses to represent individual data values. These properties are inherent in the relations between two or more raw codes—that is, in the manner in which these codes configure. For example, as indicated in the top of Figure 3, three bars in a bar chart (the individual codes) can produce an emergent feature of alignment, which is not a property of any of the individual bars in isolation. Likewise, information coded as radii from a hub may produce the emergent feature of symmetry, and a bank of angular meters may produce the emergent feature of parallelism.

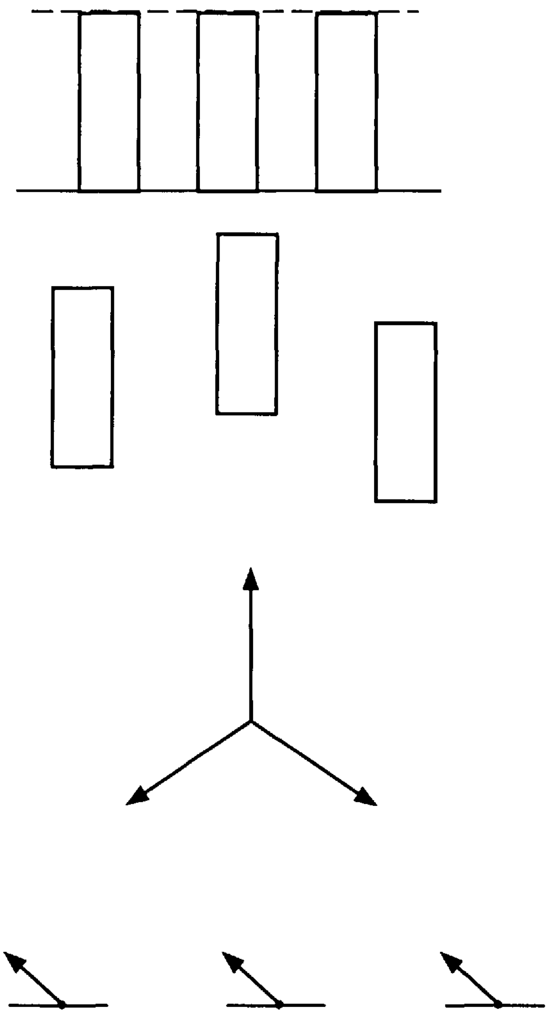


Figure 3. *The emergent feature of the top display, suggested by the dashed line, is less obviously evident in the other three display configurations.*

The importance of these and other emergent features becomes obvious when the features serve as a direct cue for a task that would otherwise require the mental computation or comparison of the individual data values. Thus a mental combination of values that must be carried out effortfully in working memory can be replaced with a perceptual operation that is carried out more or less automatically (Bennett and Flach, 1992; Vicente and Rasmussen, 1992). For example, if alignment, symmetry, or parallelism represented a special condition or state in a process control scenario (e.g., "normal"), then such a feature would serve as a valuable tool for the information integration required to determine the health of overall system functioning.

It should be emphasized, however, that the presence of emergent features in a display is, by itself, insufficient to support integration performance. The emergent feature must be carefully mapped onto variables of importance to the current task for its benefits to be realized (Pomerantz and Pristach, 1989; Sanderson et al., 1989). In Bennett and Flach's (1992) terms, this is mapping to the *semantics* of the task. In addition, some emergent features, such as the alignment of the bars, may be more salient than others, such as the symmetry of the radii or the parallelism of spatially separated meters. Clearly, the presence, salience, and mapping of emergent features are all important for the successful substitution of perceptual for cognitive processing.

We believe that most of the display proximity manipulations illustrated in Figure 2 will increase the number and/or salience of emergent features in a particular display, and efforts to configure displays (Figure 2[6]) will explicitly do so. However, unlike the proximity manipulations used to reduce IAC, which could be performed on codes of any kind (analog, digital, color), proximity manipulations intended to produce emergent features for configural displays are applicable only to analog codes. These manipulations include code homogeneity, connections, spatial proximity, attribute similarity, configurality, and some forms of object integration, and we discuss these in more detail.

Code homogeneity. The display manipulation that most strongly influences the presence of emergent features is the designer's choice of whether to mix or match analog codes across information sources (see Figure 2). The decision of whether two codes are in fact different from each other (i.e., heterogeneous) can be based on the combined work of many researchers using either physiological or psychophysical techniques to isolate the fundamental building blocks or elements of visual perception (see Treisman, 1986, for an extensive review). There is relatively strong agreement, for example, that color and form are served by different analyzers or processing mechanisms and therefore constitute heterogeneous codes. In addition, some pairings of form codes may also qualify as heterogeneous—for example, size and orientation (Treisman, 1986).

Carswell and Wickens (1990), using Pomerantz's diagnostics for emergent features (e.g., Pomerantz and Pristach, 1989), found that homogeneous pairs of codes (extent-extent, orientation-orientation, and color-color) were more likely than heterogeneous pairs (color-orientation, extent-orientation) to provide results indicative of emergent features. These results were strongest for the spatial homogeneous codes. Thus we may greatly increase the capability to capitalize on emergent features for integration performance if homogeneous codes are used.

A potential downside, however, to emergent features, particularly if they are highly salient, may involve their distracting effects when operators should instead be focusing on or using the individual codes in the display (Pomerantz and Pristach, 1989). The extent to which code homogeneity disrupts focusing may be attributable largely to the relative salience of the emergent features and component codes, just as the ability to attend to one channel may be inhibited by a salient (bright, flashing) channel in close spatial proximity. Unfortunately, the salience of the component codes may often be decreased by some of the same manipulations that increase the salience of the emergent features. In particular, the extreme spatial proximity and additional visual elements (contours, connections) used to accentuate emergent features in some displays may lead to decreased discriminability of the components through overlapping or adjacent images (see the section on disruption, clutter, and confusion, which follows).

Connections. Dashevsky (1964) provides an early example of the way connections can be used to increase the salience of emergent features. When organizing a series of circular meters, one may choose to add line segments between the meters. If these connecting lines are fixed at the same orientation as the so-called normal orientation of the pointers, then a straight line through the full array is an emergent feature depicting normalcy, and any discrepancy from the overall alignment of the pointers is accentuated.

Spatial proximity, code homogeneity, and source similarity. Increasing the source similarity or physical closeness of homogeneously coded information sources seems to be one way to increase the salience of emergent features and, therefore, create configural displays. For example, moving multiple bars in a bar chart closer together (Figure 3) may make emergent features such as alignment much easier to detect (and possibly more difficult to ignore). Likewise, if the bars are all the same color and width and oriented in the same direction, then the salience of emergent features may be increased further.

Pomerantz and Schwaitzberg (1975), using pairs of parentheses as their stimuli (Figure 2), found that subjects had greater difficulty focusing on one member of the pair as the spatial proximity of the elements was increased. In addition, classifications that required use of both members of the parenthesis pair were facilitated by greater proximity. These authors attributed performance in the close processing proximity condition to the subjects' use of an emergent feature: symmetry. Pomerantz and Garner (1973) and Garner (1978), again using parenthesis pairs, also demonstrated the importance of similarity of orientation and similarity of shape in reducing the extent to which subjects depend on the component dimensions of the stimulus (presumably, because they are using emergent features instead).

Object integration. Homogeneous codes may also be combined into a single object (Figure 2, number 5b), a manipulation that often produces several salient emergent features—for instance, the area and shape of a rectangle created by the height and width of the parallel sides (Barnett and Wickens, 1988; Cole, 1986; Wickens and Andre, 1990); the location of a single point, defined by its position in x and y space (Goettl, Wickens, and Kramer, 1991); or the size and shape of a rectangle and its location in a grid (Bennett et al., 1993). One prominent manifestation of an object-created emergent feature is the line connecting points in a line graph. The line will produce a slope that can be directly perceived, thereby signaling the magnitude of differences between the connected points (i.e., a computational integration). The line graph is found to help the integrated processing of graphs in tasks such as extracting trend information (Carswell, 1990; Carswell and Wickens, in press; Hollands and Spence, 1992; Schutz, 1961).

As with emergent features, so also with object displays; there may be a cost to focused attention or independent processing imposed by creating an object that produces emergent features. This may sometimes be a perceptual cost, as when the spatial proximity of raw codes causes one or more information sources to be masked (see the section on disruption, clutter, and confusion). However, it may also be an attentional cost, imposed because the operator shows a preference for allocating attention to the emergent feature rather than to the constituent parts (Pomerantz and Pristach, 1989).

Object Integration and Parallel Processing

Object integration with heterogeneous codes. We have seen that combining homogeneous codes into a single object will increase the number and salience of emergent features available to the user. In contrast, combining codes into a single object, whether homogeneous (e.g., a rectangle changing in height and width) or heterogeneous (e.g., creating a bar that changes length and color) may have a different benefit—one that serves tasks at all levels of task proximity equally well. This view reflects the *object file* theory of attention articulated by Kahneman and Treisman (1984; Kahneman, Treisman, and Gibbs, 1992), which suggests that all *separable* attributes of an object are perceptually processed more or less in parallel.

Whether the parallel processing benefit of combining heterogeneous dimensions into a single object is greater than the benefit for combining homogeneous dimensions cannot be asserted with certainty, but two recent studies by Carswell and Wickens suggest that this may be the case. Carswell and Wickens (1990) found that combining heterogeneous dimensions into a single object led to no cost of focusing and a significant benefit in performance for a Boolean integration task. However, if the dimensions were homogeneous, the combination led to the expected cost for focusing but to no greater benefits for integration than that observed with the heterogeneous dimensions. Carswell and Wickens (in press) used a somewhat more complex task and reached similar conclusions, finding a substantially greater benefit for object integration of heterogeneous dimensions than for that of homogeneous dimensions, for a Boolean integration task.

Thus the integration of homogeneous dimensions into objects may produce a double benefit for integration tasks. This suggests the form of the interaction in Figure lc, in which the benefits of object display to integration tasks are greater than the costs of these displays to focused attention. The two benefits are the creation of emergent features mapped to integration task requirements and the parallel processing of all dimensions. Bennett and Flach's (1992) review of 39 comparisons in the object-display literature are consistent with this view. They found strong support for the benefits of object displays in integration tasks, whereas the statistical support for object display costs was weaker (only one study showed a significant object display cost, but 30 of the studies showed trends in this direction, revealing significance when a meta-analysis perspective is taken). The diluted costs of focused attention suggest that costs attributable to emergent feature salience or close spatial proximity are often counterbalanced by advantages of parallel processing. This raises the possibility that the careful designer can craft object or configural displays that provide benefits for integration with no cost for focusing (Bennett et al., 1993).

Despite its potential to facilitate parallel processing when configured as part of a single object, we believe that heterogeneous coding, which does not lead to emergent features, should be used only with extreme caution for integration tasks. Carswell (1992) found that for a computational integration task that required comparisons, the use of heterogeneous codes seriously degraded performance regardless of whether codes were rendered in the same or separate objects. It is hard, for example, to multiply color by length (Zhang and Wickens, 1987). Furthermore, the parallel processing of attributes at early stages of processing does not rule out—and may even increase—the possibility of conflict in later stages of processing. This point is demonstrated by the well-known Stroop effect, in which color-naming performance is degraded if the subject is attempting to identify the color of a word that itself names a different color (MacLeod, 1991).

Visual Momentum: Replacing Cognitive Transformations with Perception

Visual momentum (Woods, 1984) is a technique borrowed from film editing, which tries to make the cognitive transition between two views of the same information domain as smooth as possible so that the viewer can understand how information depicted in one display can relate to that depicted in another. We suggest that many of the benefits of display augmentations that achieve visual momentum between related (task proximate) displays (Andre, Wickens, Moorman, and Boschelli, 1991; Aretz, 1991; Liang, Wickens, and Olmos, in press; Woods, 1984) are accomplished by eliminating the mental transformations (e.g., mental rotation or zooming) that were necessary in the unaugmented display to relate two different display frames.

For example, Aretz (1991) applied visual momentum design to pilot navigation with electronic maps. With a north-up electronic map, it is often difficult to comprehend how the forward field of view maps onto the terrain depicted in the map when one is heading south. Aretz found that this difficulty was greatly reduced when the angle subtended by the forward view was electronically depicted on the electronic map. Although the operation supported by providing visual momentum is not the same as providing an emergent feature (which also eliminates mental computations), it provides the same kind of benefit: reducing working memory load in translating or comparing two representations that must be compared. In this case that memory load is imposed by transformations rather than by computations. Visual momentum augmentations, creating close display proximity, should selectively benefit information integration and have little influence on independence tasks, although a possible benefit to dual-task performance could be observed.

Disruption, Clutter, and Confusion

Disruption, *clutter*, and *confusion* define a mechanism that is disruptive of performance. This disruptive influence is exerted by both relevant and irrelevant display sources and is exerted equally on the processing of sources to be integrated or to be processed independently. Its detrimental influence may be attributed to two causes.

First, when close spatial proximity (see the earlier section on information access effort and working memory) creates images that overlap and cannot be easily discriminated by source differences (e.g., distinct color or differential motion), it becomes difficult to perceptually parse, or segregate, the objects from one another. This imposes additional processing demands. Such a form of confusion will be realized whether one (focused) or both (integration and dual task) of the spatially overlapping sources are relevant to the task(s) at hand. Even when images are not overlapping but are within a degree or so of visual angle from each other, the presence of one will have a negative impact on the independent processing of the other (Eriksen and Eriksen, 1974; Kramer et al., 1991).

Second, when noise or visual clutter is close to relevant indicators (or, for a focused-attention task, to a single indicator), it will disrupt the movement of visual attention to the indicator, often imposing greater uncertainty as to where that target is located (Schons and Wickens, 1993). This latter effect is closely related to information access cost, which, as we noted, is greater with a cluttered display. Because of the greater working memory demands of integration, the disruptive effect of clutter on IAC will be greater for integration than for independence tasks. It is clear that the negative influences of confusion and clutter will be enhanced to the extent that the contributing elements are both salient (bright, distinctive) and cannot be easily discriminated from the relevant ones. (In the visual search literature, this is known as *target-distractor similarity*.) However, data also suggest that space is the most important aspect of similarity (or discrimination) in determining whether or not processing of a relevant indicator will be disrupted (e.g., Kramer et al., 1991).

Finally, just as increased proximity may disrupt focused attention, designers should be aware of the flip side of this cost: Systematically reducing the similarity of information sources can often increase the ability to focus attention on single sources. Researchers have found, for example, that the use of unique colors can enhance the ability to focus attention on the colored sources (Bennett et al., 1993; Wickens and Andre, 1990).

Summary

Collectively, the influences of the various mechanisms that underlie the interaction of the PCP are shown in Figure 4. The arrows indicate either a benefit (upward) or cost (downward) of the proposed mechanism on the task in question (thick arrows = high proximity integration; thin arrows = low proximity focused attention or independent processing). The length of the arrows represents the strength or consistency of the effect. It should be apparent that any given display manipulation could be mediated by any or all of these mechanisms. The general effect of the two middle mechanisms will be to produce the pattern of interaction defined by the PCP, but the effect of the left and right mechanisms will be to raise or lower (respectively) the overall level of performance on both tasks.

DOMAINS OF APPLICABILITY

Having identified the psychological mechanisms that underlie the PCP, we now focus on the different domains in which those mechanisms may manifest. There are two ways of considering those domains: One is in terms of the display technology (e.g., 3D displays, display layout, head-up displays), and the other is in terms of particular operational environments (the graph, the aircraft cockpit, the process

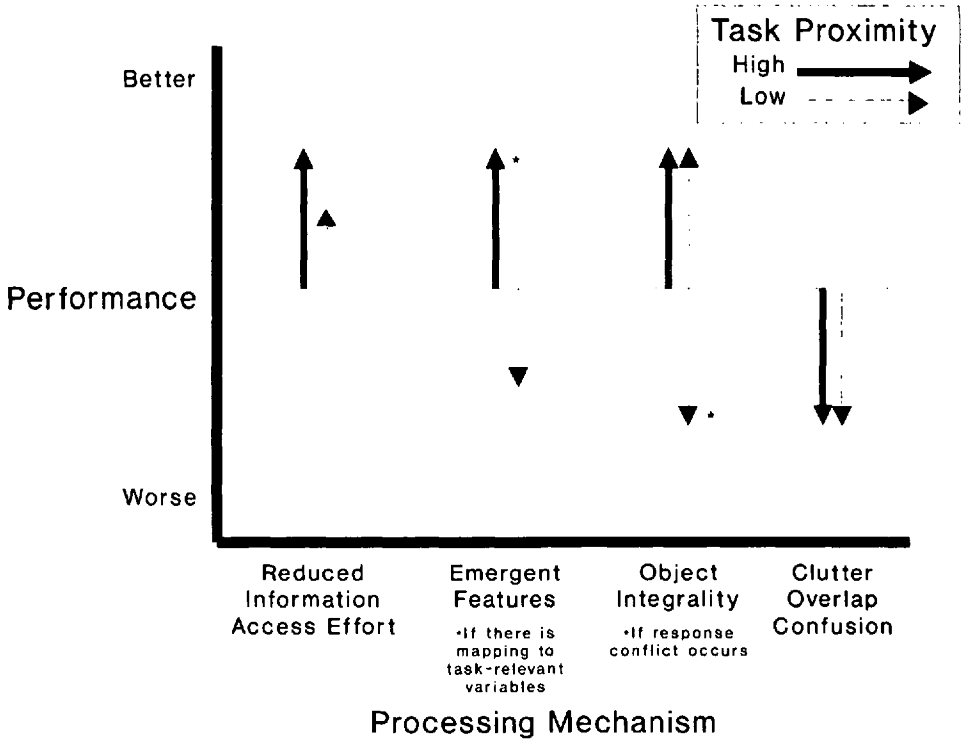


Figure 4. *The four "forces" underlying the effects observed in the PCP. The existence of different forms of the interaction, shown in Figure 1, will depend on the relative saliences of these various forces on low-proximity tasks (thin lines) and high-proximity integration tasks (thick lines). The vector lengths indicate the strength of an effect produced by a particular mechanism. In the left vectors (information access cost) the benefit is greater for the integration task because of the reduced competition with working memory. In the emergent features vector, the cost to focusing is not inevitable but will depend on the salience of, and attention given to, the emergent features.*

control display). These two ways of defining the domains are intertwined, as will be explained later. Our review of findings will partially overlap Bennett and Flach's (1992) review, and the fundamental conclusion of that analysis is that *significant benefits of object or configural integration tasks were more frequent than significant costs to focusing tasks.* The primary source of the integration benefits lies in the emergent features that object displays provide when the latter map onto integration task demands. However, Bennett and Flach's review did not consider a number of domains of applicability and dimensions of proximity that we argue are relevant to the PCP. These will be addressed in this section.

Finally, our review does not consider some important work that has compared object displays with nonobject digital displays (e.g., Coury and Boulette, 1992; Coury, Weiland, and Cuqlock-Knopp, 1992). This work is important in illuminating the strengths and weaknesses of object versus digital displays. However, in the current evaluation of proximity, the results of this work cannot be brought to bear because the dimension of proximity (object vs. separate) was redundantly varied with the dimension of format (analog vs. digital).

Graphics

Nowhere is the relevance of the PCP more direct than to the perception of graphs, in which both object integration (line graph vs. bar graph) and feature similarity (aligned vs. nonaligned representations of spatial extent) are prominent differences that are encountered across graphs. Increasingly, dimensional integration is also a feature that varies between graphs (3D vs. 2D graphics packages). Carswell's (1992) review of comparative graphics, carried out within the framework of the PCP, illustrates the robustness of the finding that more integrated perceptual representations (e.g., line graphs) tend to support more integrative cognitive tasks. The reviewed literature on which her conclusions were based will not be repeated here. Goettl et al. (1991) have demonstrated the advantages of dimensional integrality (2D point plots vs. lD bar plots) to graphical integration, as well as the costs of that integrality in focused attention tasks (reading a value on a single axis).

Some aspects of the PCP may be applicable to the processing of higher-dimensional databases in the domain of scientific visualization. For example, Wickens, Merwin, and Lin (1994) found that integrated 3D graphs depicting an *x,y,z* volume supported better performance for subjects answering complex integrative questions about a hypothetical 3D database than did two separated planar graphs depicting *x,y* and *y,z* space. Three-dimensional integrality did not support focused attention tasks. Their analysis, however, did not reveal the psychological mechanism responsible for the observed superiority. It might have resulted from emergent features (the ability to visualize the 3D constraints within the database was best supported by the 3D display), or it might have reflected reduced information access cost (the 2D display required more visual scanning between the two planar panels to locate and integrate information bearing on a given data point in *x,y* and *z,y* space).

In another visualization experiment, Liu and Wickens (1992a) observed an advantage created by an integrating "mesh" for the task of visualizing the surface of a complex data space (Figure 5). (The mesh may be thought of as the 3D extension of the connections provided by the standard 2D line graph.) This advantage can probably be attributed to the mechanism of emergent features, in that the mesh provided a more explicit representation of the convoluted surface. In contrast, the mesh presence correspondingly made focused attention on the isolated values of single points more difficult. Some indirect support for the argument that mesh assists integration performance by making emergent features more explicit is provided by the results of visualization experiments using much simpler curved (Wickens et al., 1994) or flat (Wickens and Todd, 1990) surfaces, in which surface shape

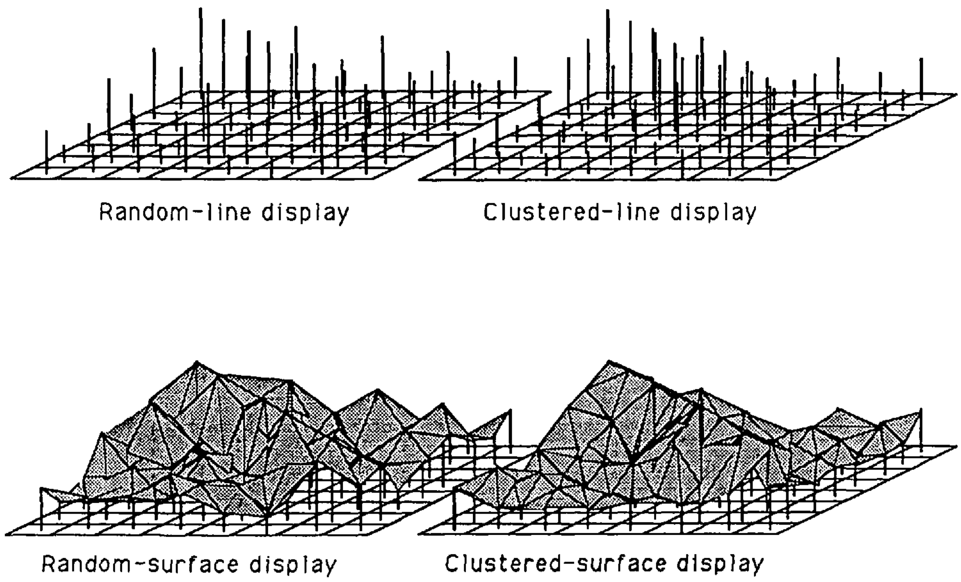


Figure 5. *Displays employed by Liu and Wickens (1992a). Top: No mesh. Bottom: Connecting mesh.*

could be more easily discerned from the position of unconnected points. Here the benefits of mesh to integration appeared to be eliminated.

Finally, the psychological mechanism of information access cost appears to lie behind another manifestation of the PCP in graph reading: the importance of close spatial proximity between the legend and the line to which it refers (Milroy and Poulton, 1978). When visual scanning and search must be undertaken to mentally "connect" a set of lines with their corresponding semantic referents (encoded within the legend), cognitive effort is expended that is likely to interfere with the cognitive processes involved in interpreting the spatial pattern of data.

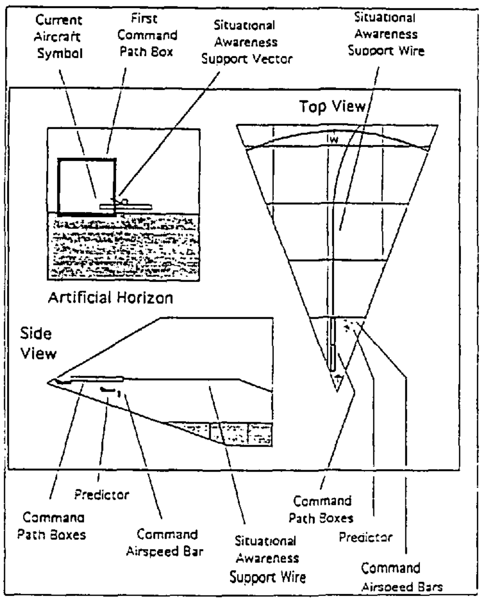
Aviation

The information needs of the airplane pilot are clearly multidimensional, considering that the aircraft has six degrees of freedom of motion and information pertaining to these may originate from a variety of display sources. Furthermore, because of the aerodynamics of most aircraft, coordinated flight requires integration across many of these axes (O'Hare and Roscoe, 1990). Hence it is easy to see how the PCP has a number of potential areas of relevance to flight deck display design. Among these are the following.

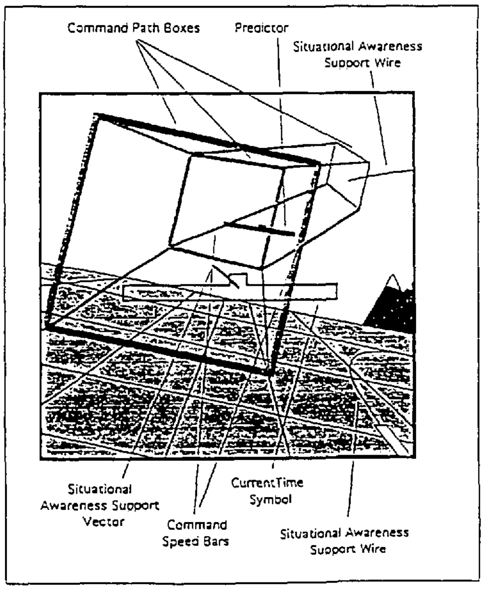
Object integration: attitude display indicator. The attitude display indicator (ADI) integrates in a single moving object (a horizon line) two attributes of information that must be integrated in coordinated flight: the pitch and roll of the aircraft, as depicted by motion of the horizon relative to a fixed aircraft symbol. This format was developed long before any explicit formalization of display integration existed, and its specific relevance to the PCP remains to be empirically examined. That is, systematic studies have not been carried out of pilots flying with a separated indicator of pitch and roll.

Dimensional integration: primary flight indicator. Several investigators have examined the viability of 3D perspective displays for conveying to the pilot information about deviations along the horizontal, vertical, and longitudinal (along track) axes of flight (for reviews, see Haskell and Wickens, 1993; Wickens and Prevett, 1995; Wickens, Todd, and Seidler, 1989). Of these studies, only Haskell and Wickens (1993) and Wickens and Prevett (1995) have explicitly compared this 3D design with a 2D planar format that was carefully crafted to contain the same information (Figure 6). In both studies the comparisons revealed substantial advantages for the 3D format in the integrated aspects of flight but some costs for tasks requiring the focus of attention on a single (along track) axis of flight. As with the visualization study carried out by Wickens et al. (1994), the specific mechanism responsible for the 3D advantage to integrated flight was not clearly revealed by Haskell and Wickens' analysis. However, analysis of the nature of the information provided by the two display formats suggests that information access cost may have been an important mediating factor. In the 2D planar format, three separate display panels needed to be scanned to acquire and integrate the critical sources of information. In particular, integration of vertical and lateral information with their respective predictor symbols had to be carried out by scanning across the three panels. In contrast, access to this information could be carried out within a single panel in the 3D display format. This reduction of information access cost with the 3D display was corroborated by a significant and substantial difference in mental workload, favoring pilots who flew with the 3D display.

The mechanism responsible for reduced performance on control of longitudinal error with the 3D display (a failure of focused attention) was assumed to relate, in part, to the fact that the location of this indicator was moving in the 3D display (considering that it was integrated with the lateral and vertical indicators), whereas it had a relatively fixed location in the 2D display. That is, processing of one dimension of an integrated object display was disrupted when there were variations in other dimensions. This disruption is related to the effect shown on the focused attention vector of object integrality in Figure 4.



(a)



(b)

Figure 6. *(a) 2D planar display and (b) 3D perspective display employed by Haskell and Wickens (1993) to represent a pilot's information needs for airport approach. Reprinted with permission.*

Head-up displays. The superimposition of instrument information on the outside scene, creating a head-up display (HUD; Weintraub and Ensing, 1992) is one of the most important manipulations of spatial proximity and is often encountered in aviation environments. Research studies that have compared head-up with head-down positioning of identically formatted information have revealed an advantage of closer (HUD) proximity that is greatest (or in some cases only observed) for information that must be integrated between the "near" domain of the display and the "far" domain of the world beyond the aircraft. This information would include, for example, imagery on the display that depicts the location or motion of features represented spatially in the world beyond (so-called conformal imagery—for example, a horizon or flight path). Electronically displayed information that is less relevant to far-domain visual information on the ground, and therefore which should be processed independently of it, is less likely to benefit from head-up presentation (Larish and Wickens, 1991; Weintraub, Haines, and Randle, 1985; Wickens and Long, 1995; Wickens, Martin-Emerson, and Larish, 1993). Using a very generic HUD simulation, Martin-Emerson and Wickens (1992) found that close spatial proximity provided benefits to both independent processing and Boolean integration tasks because of the reduction in information access cost. However, the increased benefits of close proximity were greater for the integration task.

These data are again consistent with the mechanism of information access cost in the PCP. Head-down location, imposing scanning requirements, requires greater IAC and thus will impose more of a cost if working memory must also be employed to integrate information that cannot be simultaneously viewed because of the head-down location (Figure 4, left vectors). In contrast, the costs of head-up location for information that may be processed independently is apparently the result of confusion and crosstalk created by overlapping visual images (Larish and Wickens, 1991; Neisser and Becklen, 1975) and can be eliminated once images are positioned so that they are adjacent and not superimposed (Martin-Emerson and Wickens, 1992; Figure 4, right vectors), or when the images are conformal and congruent with their far domain counterpart (Wickens and Long, 1995).

Display Layout Analysis

Close proximity in space need not necessarily create display superimposition such as found in the HUD. Indeed, a long-espoused and widely held guideline is that displays that are related should be grouped close together. Within the framework of our current analysis, the concept of relatedness is itself related to the different dimensions of task proximity described earlier. What mechanisms, then, underlie the advantage of task-related grouping? Andre and Wickens (1991) examined display layout and positioning in the context of an instrument flight simulation and found the PCP to be consistent with the data. The data suggested that it was more important to group displays close together that needed to be integrated (i.e., computational and Boolean integration), whereas it was less important to group displays that were merely used frequently (and, therefore, between which scans would be of high frequency; i.e., temporal relatedness). Here again, the specific role of reduced information access cost is implicated as the mechanism underlying the benefit of close proximity. This is because certain displays benefitted from close proximity even when they were digital and therefore would not allow emergent features to come into play (see also Vincow and Wickens, 1992).

Further evidence supporting the role of information access cost (and the competition between this effort cost and the working memory demands of integration requirements) is provided by the finding that the effects of separation between displays appear to be enhanced in a cluttered array (i.e., one containing task-irrelevant displays; Andre and Wickens, 1991; Schons and Wickens, 1993). Added clutter is known to disrupt visual scanning, whether this scanning is carried out by movement of the eyeball or by movement of an internal "attention pointer" (Thorndyke, 1980). It is evident that the costs of scanning over (or filtering out) this clutter will be greater when there are added burdens of integration. However, as shown in Figure 5 (right vectors), this detrimental effect should also be observed even when only a single display item must be identified (i.e., in focused attention), an effect that was indeed obtained by Wickens and Andre (1990).

Finally, Seidler and Wickens (1995) recently found that the added cost of working memory load amplifies the effect of "distance" through electronic space in a multifunction display (Seidler and Wickens, 1992).

Monitoring and Decision Aiding

In a variety of circumstances (e.g., chemical and nuclear process control, aviation), operators must monitor multiparameter systems and decide if parameters are out of tolerance or if their configurations reflect particular syndromes that require a unique response. Several studies have examined the PCP in these circumstances, typically comparing object displays with various forms and arrays of bar graph displays. Some of these studies have employed fairly generic monitoring tasks of input-output relations (e.g., Bennett and Flach, 1992; Beringer and Chrisman, 1991; Buttigieg and Sanderson, 1991; Carswell, 1990; Carswell and Wickens, 1987; Converse, Kozar, and Batten, 1992; Coury, Boulette, and Smith, 1989; Jones, Wickens, and Deutsch, 1990; Sanderson et al., 1989; Schmidt and Elvers, 1992). Others have attempted to map variables onto somewhat more realistic tasks with integration requirements that could represent a plausible real-world scenario. For example, Wickens and Andre (1990) considered an object display representing the aerodynamic variables that would influence the "stall safety margin" for an aircraft. Vicente and Rasmussen (1990) and Bennett et al. (1993) developed displays for an energy conversion process using emergent features to represent critical aspects of the process.

These are generally the set of experimental results that enter most heavily in the review carried out by Bennett and Flach (1992), and the details of their analysis and results will not be repeated here, except to highlight their general relation to the underlying mechanisms proposed in the second part of this paper. Specifically, when close-proximity benefits for integration tasks emerge, these are most often tied to the mapping of emergent features of high-proximity displays onto critical task parameters. Furthermore, those emergent features need not be created by object displays but can emerge out of separated but "configural" displays that share some other physical property of similarity (that is, using Carswell's [1992] terminology, they employ homogeneous spatial dimensions).

Although objects are not necessary in the formation of emergent features, object displays do tend to spawn emergent features and therefore will serve integration tasks particularly well as long as the appropriate feature-to-task mapping is implemented. Several studies (Barnett and Wickens, 1988; Bennett et al, 1993; Wickens and Andre, 1990; Zhang and Wickens, 1987) have focused on rectangle displays because the emergent feature of area perceptually depicts the product of height × width, and the feature of shape depicts the ratio of the two dimensions. This seems to be a desirable property because of the propensity with which products of and ratios between parameters define task-related integrations in many real systems (e.g., distance or amount = rate × time; see also Cole, 1986).

In one important circumstance, an object display benefit may emerge in decision/monitoring tasks that is not related to emergent features: when objects with heterogeneous features are monitored (e.g., Edgell and Morrissey, 1992; Zhang and Wickens, 1987). As we noted earlier, color and size, for example, cannot configure to form an emergent feature. However, for Boolean integration tasks, which require a response if some logical combination of the two variables is present, benefits of object displays appear to emerge. For example, one could envision an object display benefit in caution/advisory warning indicators in which the color of the object indicates one feature of the potentially malfunctioning system component, the location indicates a second feature, and the flash rate indicates a third feature (e.g., urgency).

As we have noted, however, it appears that such object benefits do not differentially favor integration over independence tasks but, rather, will be likely to affect both equally. In this sense it might be argued that object integration of heterogeneous dimensions often achieves its benefits via reduced information access cost. If scanning between objects is serial and processing of dimensions within objects is parallel (Kahneman and Treisman, 1984), then recoding the same two or more variables as dimensions of a single object will reduce effortful scanning (or internal attention movement). This in turn suggests that heterogeneous object benefits are most likely to be observed in cluttered, multielement displays (e.g., an instrument warning panel).

CONCLUSION

Analysis of the variety of data and mechanisms underlying the PCP suggests that several of these support integration, whereas a smaller number penalize focused attention and independent processing. If these mechanisms are separate and independent from one another, as their description in the second part of this paper suggests, then it is not surprising that the review by Bennett and Flach (1992) reveals far more instances of high-proximity benefits to integration than of high-proximity costs to focused attention. As a consequence, it is not surprising that the "strong form" of the PCP interaction, shown in Figure la, does not emerge from many experimental results.

It is then reasonable to ask whether this conclusion, and the multiplicity of mechanisms argued to be responsible for the PCP, dilutes the explanatory and predictive power of the principle as a design tool. In a sense this is probably the case, even as, ironically, it broadens its generalizability. The view of the PCP that we espouse here is analogous to emerging views of intelligence (Sternberg, 1985), attention (Parasuraman and Davies, 1984; Wickens, 1992), and single-channel theory (Broadbent, 1972). In these instances a single construct was proposed that, on closer scrutiny, began to reveal an increasing number of different processing mechanisms underlying its general manifestations in human performance (e.g., different dimensions of abilities, mechanisms of attention, and forms of processing bottlenecks, respectively). Did this fact dilute the explanatory value of the concepts?

Again the answer is ambivalent. The result was certainly a realization that life (and human behavior) is far from simple. But it also revealed that the terms *intelligence, attention*, and *single channel* served as general rubrics for the study and understanding of a wide variety of subconstructs, the values of which have been appreciated by both researchers and practitioners. Furthermore, the constructs also spawned series of experiments, many of them healthily critical, which themselves shed insight into the nature of the processes (i.e., intellectual activity, multiple-task performance). In the present case of the PCP, we believe that a renewed vigor of investigation into the nature of information integration and its dependence on display formatting has been the result.

Regarding the PCP, at least four key concepts have emerged from the componential analyses of processing mechanisms described in this article, each of which has potential utility for display design:

1. *Emergent features:* their relationship to homogeneous feature displays; increases in their salience resulting from proximity, attribute similarity, and object integration; and their requirement for mapping onto task-related variables (as noted, our conclusions here strongly reinforce those of Bennett and Flach [1992] and Bennett et al. [1993] in their discussion of configural displays).
2. *Information access cost* and its negative interaction with working memory demands, which in turn are often amplified when integration is required between the two or more sources that must be accessed.
3. *Object displays*, which will have qualitatively different effects when produced by homogeneous rather than heterogeneous features.
4. *Confusion and clutter effects* resulting from close proximity either between relevant and irrelevant (i.e., clutter) sources or between overlapping images.

Like Bennett and Flach (1992), we consider the understanding of and distinction between so-called lower-order variables and higher-order variables to be crucial in supporting different aspects of task performance. The former are more likely to require greater focus of attention on isolated components of a multiparameter system; the latter are more likely to require integration across multiple components. We also argue that, ideally, displays should be able to support the processing of both kinds of variables (see also Vicente and Rasmussen, 1992). However, because of the processing mechanisms described in this article, certain trade-offs in support of one or the other may exist. Good understanding and judicious use of the principles may enable the designer to capture the best of both worlds (see Bennett et al., 1993; Wickens and Andre, 1990).

Alternatively, based on the relative frequency and urgency with which operators may need to access higher-level (integrated) or lower-level variables, a decision may be made to implement a design that maximizes the principles that support processing of one or the other class of variable, even if that principle-based design may fail to enhance (or even degrade) processing of the other kind. We believe that our componential analyses of the PCP offer guidance in these design decisions that is complementary to, rather than in conflict with, the semantic mapping principle characterizing Bennett and Flach's (1992) approach.

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