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**HUMAN PERFORMANCE CENTER  
DEPARTMENT OF PSYCHOLOGY**

**The University of Michigan, Ann Arbor**

***The Development and  
Utilization of Integrated  
Multidimensional Displays:***

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FINAL REPORT

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displays and their compatibilities with human perceptual abilities. Further, it was our goal to develop a comprehensive theory of multidimensional integrality as well as methodological techniques to investigate these questions. During the four and a half years of the contract's duration nine technical reports were issued and two more reports are in preparation. These detail the various empirical and theoretical pursuits of the principal investigator and his colleagues. A bibliography of these technical reports is appended. In addition to these written reports, contract work was reported orally at 16 scientific meetings and conferences.

The research supported by the contract is presented under four major headings: (a) preliminary analyses of dimensional integrality, (b) necessary methodological developments for the study of integrality, (c) empirical findings and theoretical development, and (d) work in preparation.

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University of Michigan and the Engineering Psychology Programs,  
Office of Naval Research.

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- II. The purpose of this contract was to establish a program of research that would lead to basic facts about the nature of complex integrated multidimensional displays and their compatibilities with human perceptual abilities. Further, it was our goal to develop a comprehensive theory of multidimensional integrality as well as methodological techniques to investigate these questions. During the four and a half years of the contract's duration nine technical reports were issued and two more reports are in preparation. These detail the various empirical and theoretical pursuits of the principal investigator and his colleagues. A bibliography of these technical reports is appended. In addition to these written reports contract work was reported orally at 16 scientific meetings and conferences.
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A) Preliminary Analyses of Dimensional Integrality

At the time that our project began, research concerned with integration of information in visual displays was reasonably extensive. What was lacking was a theoretical framework in which to embed much of this experimentation. As a consequence it was difficult to conceive of new experiments that would lead to new directions for research. The major framework that existed in 1976 was that developed much earlier by Garner which defined integrality by means of a complex set of converging operations. The most important of these was the definition of integral dimensions as those that yielded decrements in speeded classification when filtering performance was required (i.e. separating relevant from irrelevant information) and which yielded improvement in performance when classification was based on dimensions that were correlated across stimuli. A second definitional basis for integral dimensions involved the psychophysical criterion of the multidimensional scaling metric: Integral dimensions were best scaled with a Euclidean metric while separable dimensions were best scaled with the City Block metric. The initial phase of our project entailed the critical examination of these concepts.

1. Somers, P., & Pachella, R.G. Interference Among Sources of Information in Complex Integrated Displays (Technical Report 58). This report examined various causes of interference in complex displays. The concept of integrality was carefully distinguished from interference due to masking and distraction that can take place in multidimensional displays. Two forms of dimensional relationships were defined as leading to interference that could be reasonably called integrality: Combination of dimensions and interaction of other dimensions. Two dimensions of a stimulus interact if the perception of one dimension varies systematically with the level of the other dimension. Two dimensions might interact but still be separable when the observer's task does not involve a resource limitation (i.e. pressure to respond quickly). To the extent that a perceiver cannot separate or filter under any circumstances the dimensions are said to be combined. Thus, combination and interaction can be distinguished on the basis of comparisons of speeded and unspeeded performances. A method for measuring combination by requiring filtering in a similarity judgment task was developed and a demonstration experiment was performed.
2. Hardzinski, M., & Pachella, R.G. A Psychophysical Analysis of Complex Integrated Displays (Technical Report 59). This report examined a number of empirical results that can be obtained with the multidimensional scaling of complex displays. Five types of complex integrated display types were subjected to multidimensional scaling analyses. The display types were selected to be representative of a variety of characteristics that can result when dimensions are combined in an integrated fashion. These characteristics included perceptual separability, familiarity, emergent properties and perceptual interactions among dimensions. Of primary interest was the question of whether or not the Minkowski scaling metric would be diagnostic or predictive of any of these characteristics, as previous literature had indicated. The results indicated that in virtually all cases the Euclidean metric produced better

fits than the City Block metric and thus, the Minkowski metric could not be diagnostic for the basic varieties of integrality that we were able to isolate. The qualitative interpretability of the individual dimensions of the display proved to be of much greater utility for assessing perceptual characteristics. The report presented representative analyses of individual observer data and also discussed the implications of the results for display design.

B) Necessary Methodological Developments For the Study of Integrality.

Our preliminary studies of the status of research on integrality lead to the conclusion that much of what passed for theoretical work was based on the inadequate use of certain aspects of multidimensional scaling techniques. Within our project we decided to develop new and substantially more sophisticated properties of multidimensional scaling configurations for the theoretical diagnosis of integrality. This work involved the mathematical analysis of multidimensional scaling techniques, the development of new computer algorithms for the production of scaling configurations and the application of these programs to empirical data sets large enough and systematic enough to test the utility of these programs.

1. Noma, E., & Johnson, J. Constraining Nonmetric Multidimensional Scaling Configurations (Technical Report 60). The interpretation of multidimensional scaling outputs entails the conversion of observer judgments into a geometric pattern or configuration. It further involves the labeling and identification of geometric structures of the geometric spaces in which these configurations are embedded. This report reviewed some of the most commonly used geometric structures. These commonly used structures require many mathematical and psychological assumptions including the assumption that the configuration produced by a scaling program with the lowest stress is the desired output. Unfortunately, little was previously known about the uniqueness of a configuration that is generated from fallible data. The potential non-uniqueness could most obviously affect the interpretation of spatial outputs of scaling programs. What we needed to explore were the possible alternative spatial configurations that might lead to the same stress values as that produced by current scaling programs. Furthermore, we needed to develop techniques that would allow us to constrain scaling configurations to have properties that we desired a priori in order to see if they differed systematically from the lowest stress configuration produced by a typical scaling program. The present report examined these questions with a tutorial emphasis.
2. Noma, E. Interession Variability and Stress: A Monte Carlo Study (Technical Report 63). Two Monte Carlo studies explored the relation of the tau measure of interession response variability and the stress measure of the corresponding multidimensional scaling solution for the same set of data. This provided a statistical basis for evaluating the goodness-of-fit of a spatial configuration. In the first Monte Carlo study, the stress and tau measures for 10, 16, and 30 point configurations in 1, 2, 3, and 4 dimensional spaces were shown to be linear functions of the internal error level. In the second study,

these relations were shown to be relatively invariant with respect to the shape and spatial characteristics of the particular configurations. Three methods were proposed for establishing acceptable levels of stress for heuristic and for constrained multidimensional scaling. In one method, tau is used to predict the mean stress using appropriate equations. The empirical mean stress must fall within specified confidence bounds for the configuration to be acceptable. In the second method varying amounts of error are added to the inter-point distances of the scaled configuration to determine the error-stress curve. Assuming this curve to be linear within a reasonable range of error values the error value for the empirical stress is derived from the regression equation. In the third method, previous Monte Carlo studies are first used to estimate the error level given the mean stress. This error level is then used, as in the second method, to determine an acceptable range of taus.

3. Noma, E., & Johnson, J. Constrained Nonmetric Multidimensional Scaling (Technical Report 62). The typical multidimensional program produces a scaling configuration that attempts to minimize the goodness-of-fit measure called stress. As noted in Technical Report 60 little is known about the uniqueness of the configuration as generated from fallible data. The present report developed a new scaling technique called CONSCAL that allows the examination of this uniqueness by constraining the configurational output of the program to conform to a particular psychological model. The implications of this approach for interpreting scaling outputs and for model testing in general are discussed. Of particular importance to our project, this technique allowed us to see if particular configurational shapes (e.g. rectangular) differed systematically from the minimum stress configuration. Thus, we could conclude whether or not certain sets of judgments of observers would meet certain desired psychological properties.

#### C) Empirical Findings and Theoretical Development

The major contribution of the present project was the development of a comprehensive theory of dimensional integrality. This theory, which we call the theory of psychophysical compatibility, differs from the earlier approaches to integrality by using psychophysical properties to predict the result of selective attention experiments utilizing either integral or separable dimensions (as defined psychophysically). The theory suggests that integrality is a property of the mapping of physical dimensions into the perceivable psychological attributes of the stimuli. When the physical description of a set of stimuli is chosen in such a way that it corresponds to the perceivable attributes of the stimuli, the stimuli will produce selective attention results that look like those obtained with "separable" dimensions. Low correspondence between the physical and psychological attributes of a set of stimuli will lead to results in selective attention experiments that would be called "integral". The most significant work within the project involved the empirical testing of this theoretical approach and the establishment of its applicability and its limitations.

1. Somers, P. Perceptual Interaction Between Stimulus Dimensions as a Basis of Dimensional Integrality (Technical Report 61). (AD A064867)  
This paper describes and tests a new psychological theory of dimensional integrality. Integrality refers to the phenomenon of physically independent dimensions appearing fused into a single perceptual attribute such that the physically separable dimensions are not perceptually separable. The theory proposes that all stimuli are perceived as combinations of perceptually independent dimensions, but that for integral stimulus sets the perceptual dimensions do not correspond to the physically independent dimensions. Integrality is demonstrated psychophysically by interaction in psychological similarity space between physically independent dimensions.

Interactive and non-interactive stimulus sets from the same stimulus domain were developed. Similarity judgments indicated that observers perceived both sets using the same pair of perceptual dimensions.

The theory's predictions on speeded classification of interactive and non-interactive stimulus sets were tested. Interacting dimensions produced results in speeded classification tasks typical of phenominal integrality. First, when compared to the baseline of unidimensional classification, reaction time increased in a "filtering" task, a task requiring selective attention to the dimension as the stimuli varied independently on two dimensions. Amount of interference correlated highly with degree of interaction. Second, observers gained in speed in a task requiring discrimination between two stimuli which differ from each other on two dimensions. Reaction time was directly related to perceived similarity between stimuli--the more similar the pair, the slower the response. This relationship was demonstrated by a difference between speed gain for positively correlated and negatively correlated pairs, consistent with the form of the dimensional interaction.

With non-interacting dimensions, interference in "filtering" and speed gain in classification of correlated pairs correlated highly with the degree to which the dimension irrelevant to classification was more discriminable than the relevant dimension.

It was concluded that speeded classification performance is best predicted by the psychophysical structure of the stimulus set. The demonstrated relationship between classification reaction time and both interaction and relative discriminability of the dimensions suggested that the study of integrality can be beneficially redefined as a direct analysis of the psychophysics of dimensions.

2. Cheng, P.W. A Psychophysical Approach to Form Perception: Incompatibility as an Explanation of Integrality (Technical Report 65).  
Integrality refers to an apparent difference in the perceived distinctiveness of visual dimensions. Some combinations of physically independent dimensions appear to fuse into a single perceptual attribute, while other combinations appear to leave the physically independent dimensions perceptually distinct. This apparent difference

in the perceived distinctiveness of visual dimensions have previously been explained by the postulation of two types of internal representations. One type is assumed to have a similarity (integral) structure, while the other type is assumed to have a dimensional (separable) structure. To define these two types of structures, a set of converging operations has been proposed, including a pattern of performance in speeded sorting. However, the pattern has not always been found to fall neatly into two categories. In particular, degrees of integrality and asymmetric integrality have been observed.

This report attempts to show that two crucial operations defining integrality--interference and condensation time in speeded sorting--as well as degrees of integrality and asymmetric integrality can result from a single type of structure, the dimensional type. It attempts to show that these patterns of performance can be explained by the compatibility of physical dimensions with psychological (i.e. separable) dimensions.

Experiment I showed that a psychophysically compatible dimension did not produce interference, whereas psychophysically incompatible dimensions did, as predicted by the psychophysical compatibility theory. In this experiment, compatibility was defined by the compellingness of dimensions. Experiment II showed that degrees of compatibility (as defined by the orientations of sets of stimuli in a multidimensional scaling representation of similarity judgments) could explain the occurrence of interference, the inverse relationship between interference and condensation time, and degrees of integrality (as indicated by gradations of the pattern of interference and condensation time). Experiment III attempted to show that in accordance with the compatibility theory, the compatibility of single dimensions can generally be evaluated independently of the compatibility of concomitantly varied dimensions. This independence implies that if one manipulated dimension is psychophysically compatible while another is not, asymmetric integrality will result. In this experiment, the compatibility of a dimension was evaluated in the context of two irrelevant dimensions, as well as with different values along the same irrelevant dimensions. Compatibility was defined phenomenologically as well as by the amount of interference. Results showed that the compatibility of a dimension was not consistently affected by variation along other dimensions.

In addition to the above, this report explored the metric property of rectangularity--a potential systematic definition of psychophysically compatible dimensions. Rectangularity refers to the shape of the multidimensional configurations derived from judgments of the overall similarity of pairs of stimuli. If stimuli of equal difference along physical dimensions are judged equally dissimilar regardless of values along other physical dimensions, then rectangularity will obtain. It was concluded that rectangularity is not a sufficient definition of compatible dimensions, and it was tentatively concluded that it is not a necessary definition of compatible dimensions.

The results obtained at least imply that Garner's definition of integrality is inadequate. In place of his definition, two new operations were proposed: The effect of dimensional within-class variability with appropriate controls, and the effect of the orientation of a fixed configuration. The findings furthermore imply that a single type of internal representation (the dimensional type) may account for integrality and separability.

3. Benjamin, J. & Pachella, R.C. The Effect of Complexity in Integrated Multidimensional Displays (Technical Report 66). This report extends the findings of the previous experiments (Technical Reports 61 and 65) by demonstrating that irrelevant information can also interfere with the perceptibility of display dimensions. The effect is mediated by the salience of the irrelevant information and not its amount per se. In the terminology of the present project, the potential for irrelevant information to interfere with relevant information depends upon whether the physical attributes in question are integral, whether they combine with or modify the salient features of the display. In the experiment the total number of irrelevant features was systematically varied in a complex set of displays for which observers were asked to make pairwise similarity judgments. The results showed that observers could not ignore irrelevant distinctive information even under strong instructions to do so, although they could ignore common irrelevant features. Thus, the relations between the relevant and the irrelevant information rather than the amount of information is the critical factor.
4. Pachella, R.G., Somers, P., & Hardzinski, M. A Psychophysical Approach to Dimensional Integrality (Technical Report 64). This paper presents a coherent summary of the theoretical position that is the core of the work of this project. It presents the essential arguments that allow us to distinguish integral from separable dimensions; it shows how these psychophysical properties can be used to predict the performance in selective attention experiments that had previously been used to define integrality; and furthermore shows how this approach is related to other general theoretical positions. Finally, using data previously gathered from the project it demonstrates how this definition of integrality is validated against standard information processing tasks involving speeded classification.

D) Work Still in Progress

Two major projects have been completed with regard to the collection of data but the data have not yet been fully analyzed and the Technical Reports have not been written. Since these are large projects the analysis of data and writing will undoubtedly take a considerable amount of time. Because of the importance of this work to our efforts in the past year of the project we will briefly mention this research here and acknowledge that any reports or publication arising from these experiments will carry the usual footnote acknowledging the support of our contract.

1. Patterns of Interference in Integrated Displays under Conditions of Spatial Uncertainty. This study examines the role of spatial uncertainty of displayed information as a source of interference in multi-dimensional displays. The major hypothesis is that display integrality and the global features of a display will have much larger effects in situations where the exact location of relevant information on the display is unknown to the observer. Where spatial uncertainty is minimized, integrality may play a less important role. Additionally, the experiments are designed to discover if the pattern of interference is the result of the automatic operation of certain aspects of the perceptual system. Alternatively, interference may be the result of the operation of perceptual control processes.
  
2. The Separation of the Effects of Relative Discriminability and Psychophysical Compatibility in Integrated Multidimensional Displays. These experiments attempt to disentangle the interference that can be attributed to psychophysical compatibility, the major effect that our project has focused upon, and interference that has a more directly attentional basis. This has been done by systematically varying the relative discriminability of the relevant and irrelevant information in the display presented to observers. Once the effects of the known factor of compatibility have been removed there is still interference that can be demonstrated in classification experiments. This interference can only be attributed to some form of attentional mechanisms. The problem with much previous research which attempts to study these mechanisms is that they have not done the appropriate scaling of stimulus materials in order to account for the effects of dimensional interaction that have been discovered in our project. Thus, these experiments should provide a more diagnostic data base than has been available before.

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