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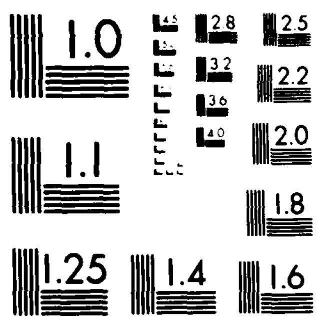

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A Comparison of Homogeneous and Heterogeneous Display Formats in Information Integration and Nonintegration Tasks

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The multiple resources model states that dual-task performance improves if the component tasks are made minimally similar with respect to the mental resources they demand. The lesser the overlap between stimulus modality, central processing, and response modality resources, the lesser the predicted interference between concurrent tasks. Although the model has generally received support from dual-task experiments, it has not been known whether it generalizes to task environments requiring the combination or integration

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of information sources prior to response.

Here two experiments made use of three tasks varying in terms of integration demands, and presented via four visual display formats for numeric information, presumably varying in the homogeneity of resource demands. The display indicators were bargraphs and the word names of digits (e.g., "nine"), and the formats were pairs of indicators: bargraph-bargraph and word-word (homogeneous displays), and bargraph-word and word-bargraph (heterogeneous displays).

In Experiment 1 the three task configurations required: (1) a separate response to each indicator (dual task): judgment if each is 5 or more; (2) central processing integration (ADD task): judgment if the sum of the two numbers was 5 or more; (3) response integration (OR task): judgment if either number was 5 or more. In support of the hypothesis that integrated tasks will be better served by homogeneous display formats using common resources, the error data indicated better performance with the homogeneous displays in the ADD and OR tasks, but better performance with the heterogeneous displays in the dual task. Latency data did not reliably differentiate the tasks with respect to displays.

In Experiment 2 the dual task configuration was redesigned to make the two tasks more different: notably a 5-or-more judgment for one indicator, an odd-even judgment for the other. The ADD and OR tasks were the same as before. The latency data from Experiment 2 supported the hypotheses: the integrated OR task was better served by the homogeneous display, and the separate dual tasks were better served by the heterogeneous displays. The ADD task was indifferent to display format.

In addition, the data for the dual task condition of both experiments showed a redundancy gain--an RT advantage when both displays contained similar information. This effect was only observed with heterogeneous displays, a result interpreted as supporting greater parallel processing for heterogeneous displays.

These results conceptually replicate previous findings in showing that dual-task environments benefit from the use of nonoverlapping (heterogeneous) resources, presumably because they allow for greater noninterfering parallel processing. Yet when information integration is required, this is no longer true; under certain conditions, benefit is obtained when the information sources to be integrated use overlapping (homogeneous) resources. It appears that the design of optimal displays in applied settings must take into account the degree to which information is to be integrated or responded to separately.

Abstract

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A Comparison of Homogeneous and Heterogeneous Display Formats in Information Integration and Nonintegration Tasks

David B. Boles and Christopher D. Wickens

According to the multiple resource model of human performance (Wickens, 1980, 1984), there are three fundamental dimensions along which mental processes may typically be classified. The first dimension, that of modality, refers to the sensory system impinged upon by a stimulus. The second, that of central processing codes, refers to the cognitive operation required for meaningful response to the stimulus, and in practice is described in terms of a verbal-spatial processing distinction. The third dimension is that of processing stages, and contrasts processes involved in perception and working memory with those involved in responding.

One of the successes of the multiple resources model has been in predicting patterns of interference between two competing tasks. In general it may be said that there is minimal interference in dual-task environments when the tasks are minimally similar with respect to the resources they demand (Allport, Antonis, & Reynolds, 1972; Wickens & Sandry, 1982; Wickens, Sandry, & Vidulich, 1983). Thus Wickens & Sandry (1982) in one experiment found that a spatial Sternberg memory search task requiring memory of dot patterns was interfered with more by tracking (also involving spatial processes) than by a word memory task (involving verbal processes). By contrast, this pattern was reversed when a verbal Sternberg task was used in which letters were remembered. Greater overlap in resources therefore produced greater interference between tasks.

Since actual task environments frequently require the simultaneous or near-simultaneous execution of more than one decision process, it is clear that dual-task research is of importance in applying cognitive principles to practical settings. However, we are concerned that too narrow a focus on dual-task issues ignores quite a different problem of equal importance. This is the problem of how information displays should be constructed so that the operator can integrate information across more than one source, in order to minimize decision latencies and errors. In a real sense, the integration problem involves the combination of two or more information sources into one response, instead of (as in the dual-task environment) two sources of information into two responses. It is important as a problem because many practical settings require extensive integration of information: for example, air traffic control demands the integration of altitude with X-Y vector information (and of one plane's vector with another), and nuclear control requires that temperature, pressure, and other information be combined to allow decisions about the state of the generating plant (Danaher, 1980; Goodstein, 1981; Moray, 1980; Sheridan, 1981).

What can be said about the optimal design of information displays for integration situations? An extrapolation from the multiple resources model would seem to imply benefit from the use of separate resources, and thus of different modalities and cognitive processes to extract the information. However, since the model was designed to apply to dual-task situations, this prediction is by no means clear: to the contrary, it could be that the use of separate resources facilitates the independent processing of information sources to the extent that they become difficult to integrate. If so, then employment of similar resources could be desirable since it should encourage the integration of information. From another viewpoint, a similar prediction can be made if it is assumed that the time to switch attention from one source to another is less when the information is in the same format than differing formats (LaBerge, Van Gilder & Yellott, 1971), although this viewpoint appears to predict the same for nonintegration conditions. A theoretical review elaborating some of these points and placing the integration problem in a wider context is described in Wickens & Boles (1983).

To begin investigating the integration issue, we designed three numerical judgment tasks to vary along a nonintegration-integration dimension. One was a dual-task condition requiring separate judgments and responses to two visual numerical indicators, representing nonintegration. The second task required that the indicator numbers be added together prior to a single response, representing "central integration" since common processing of the indicators presumably began during central processing. The third task was a "response integration" condition requiring that the indicators be judged separately but that one response be selected using a decision rule. It was hoped that by comparing the three tasks, it would be possible to establish whether the optimal display format for information integration differs from that required by nonintegration, and if so, whether the stage of processing at which information is integrated makes a difference.

Variation of display format was possible through the use of spatial and verbal numerical indicators, represented by bargraphs and the word names of digits (e.g., "five"). In the framework of the multiple resources model, these are assumed to demand separate processing resources. Homogeneous (same format) displays used either all bargraphs or all words, while heterogeneous (different format) displays mixed the two.

EXPERIMENT 1

Method

Subjects. Twenty-four undergraduate student volunteers participated in a single one-hour session, receiving payment for their services. All were self-classified right-handers. With task made a between-subject variable, four males and four females served in each task.

Apparatus and stimuli. Stimuli were presented on an Apple III monitor with a P4 phosphor, controlled by an Apple II Plus microcomputer, which was modified to synchronize stimulus presentations with the monitor's raster scan and to provide blanking of the screen while writing was done in memory (Reed, 1979). Pascal was the programming language. Reaction time responses (with msec accuracy) were collected from external keyboards using a California Computer Systems 7440A Programable Timer card and 7720A Parallel Interface card. Keyboards were constructed with two keys apiece, one key farther and one closer to the subject, in these experiments operated by the forefinger and thumb of one hand respectively.

Stimulus displays consisted of the punctate presentation of two numerical indicators. A verbal indicator was the the word name of a digit between one and nine inclusive, and was presented in upper-case letters and vertical orientation, subtending 0.5 degrees horizontally and from 2.4 to 4.0 degrees vertically. A spatial indicator was a vertical bargraph consisting of a rectangular box whose height corresponded to an integer value between one and nine inclusive, accompanied by three horizontal reference lines representing values of zero, five, and ten units. The width of the bar or rectangle was 0.6 degrees, the horizontal length of the reference lines was 1.5 degrees, and the height of the bar was from 0.4 to 3.6 degrees. Figure 1 shows an example of each indicator type.

When presented, one indicator was shown simultaneously to each side of a central fixation point. The side closer to fixation was 2.4 and 2.1 degrees for words and bargraphs respectively. All four pairings of the indicators were used in a blocked design: word-word, word-bargraph, bargraph-word, and bargraph-bargraph. However, the particular numerical values displayed were chosen with task and response probability considerations in mind; this is described for each task separately below.

<u>Task procedures.</u> The particular procedure used varied depending on task demands.

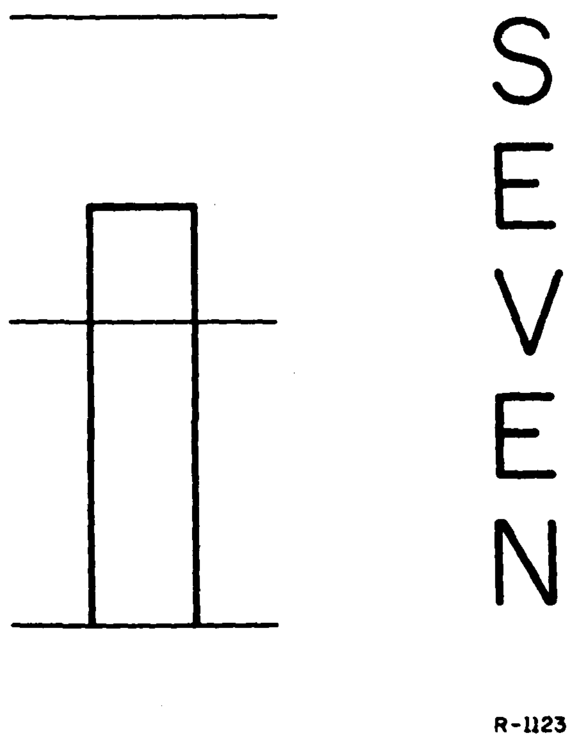

Figure 1: Bargraph and word examples.

(1) "Both" task (nonintegration). In this task, the subject responded separately to the two indicators. The object was to judge whether each indicator showed a value of five or more, and using a specified response order, to emit a speeded response for one and a second, unspeeded response for the other. Half the subjects responded to the left indicator first using the left hand and a keyboard placed slightly to the left, following this response with one to the right indicator using the right hand and a keyboard slightly to the right. This response order was reversed for the remaining subjects. Responses were always two-choice, involving either a "five-or-more" (yes) decision with the forefinger, or a "less-than-five" (no) decision with the thumb.

Stimulus pairs were randomly preselected so that three required two yes responses (5,6; 6,7; 7,8), three required two no responses (1,3; 1,4; 2,3), and six required a mixed response sequence (1,5; 1,6; 2,5; 3,8; 4,6; 4,8). Both orders of these pairs were used, resulting in 24 ordered pairs in which yes and no responses were equiprobable, and in which the first and second responses were orthogonal.

(2) "Add" task (central integration). In the add task, subjects mentally added the two indicator numbers together to produce one response. The object was to judge whether the added numbers equalled ten or more (a yes response) or less than ten (a no response). Half the subjects used the left hand to respond, and half used the right hand.

In this instance, stimulus pairs were randomly selected so that half required a yes response (3,8; 3,9; 4,9; 5,6; 5,7; 6,8) and half required a no response (1,2; 1,6; 2,4; 2,5; 3,6; 4,5). Again, both orders of the pairs were used, as in the other tasks.

(3) "Or" task (response integration). Subjects decided whether either indicator number was five or more (a yes response). If both were less than five, a no response was required. Response hand was balanced across subjects.

Half the randomly selected stimulus pairs required a yes response (1,9; 2,9; 4,5; 4,7; 4,9; 6,8), while half required a no response (1,2; 1,3; 1,4; 2,3; 2,4; 3,4).

General procedure. The three tasks were assigned to different groups of subjects, with four males and four females performing each task, and with response variables balanced within each sex. Instructions to subjects included emphasis on the nature of the task, the necessity of fixating the central fixation point (a small cross), and the means of making a response. Subjects were told to respond as fast as possible, but also to make as few errors as possible. However, in the "both" task it was emphasized that the second response was untimed and that only its accuracy was important. Before each of the four display conditions a card was shown to the subject, on which was drawn a representation of a typical display (e.g, a bargraph and a word).

A trial had the following timeline. First a small central fixation cross appeared for 750 msec, followed by a 100 msec blank interval and then a stimulus display shown for 150 msec. A response was then collected, or else a 5 sec deadline was passed. This was followed either by 100 msec of blank interval and then the next trial, or (in the case of the "both" task) by the message "2ND RESPONSE?" and the collection of a second response (also within a 5 sec deadline), and then the blank interval and next trial.

Trials were organized into blocks of 48, representing 24 ordered stimulus pairs presented twice each in a random order unique to each subject. For each display type, one practice block was given, followed by two experimental blocks, with the order of the four display types determined by Latin square design. The order was then reversed for the second half of the session (but with no practice blocks), resulting in a total of 4 experimental blocks (192 trials) per display type. In all cases, the data stored by the computer consisted of codes giving the ordered pair shown, the response given by the subject, and the reaction time. For the "both" task, the second response given by the subject was also recorded, but such responses were not in fact analyzed.

Results

For each subject, median RTs and percent errors were calculated for each display type. Initial analyses for both dependent measures showed prominant sequence (largely practice) effects in each, in spite of the "reversed Latin square" balancing procedure. Accordingly it was necessary to correct statistically for such effects. This was achieved by calculating the grand mean for each Latin square (one per four subjects), and then adding or subtracting constant amounts to each subject's sequential conditions to bring the marginal means to the level of the grand mean. For example, in the "or" task Latin square for right-hand responders, the grand mean was 505 msec, and the marginal means for the eight sequential pairs of blocks (collapsed over display type) were 568, 542, 524, 486, 475, 491, 489, and 466 msec respectively. Thus within the square, 63 msec was subtracted from each subject's first pair of blocks (568 less 505), 37 msec was subtracted from the second pair, and so on through the last pair, to which 39 msec was added. Since across the four subjects in a square, all display types were equally represented at each place in the sequence, this procedure leaves condition means unchanged, but greatly reduces "error" variance by removing much of the variance due to systematic sequence effects.

Adjusted medians were then further collapsed into homogeneous vs. heterogeneous conditions, homogeneous conditions being two bargraphs or two words, and heterogeneous conditions being mixtures of the two. The rationale for this is that only after collapsing the results do the homogeneous and heterogeneous displays become comparable, with both bargraphs and words equally represented in each. Finally, the RT and error results were subjected to Task ("both" vs. "add" vs. "or") by Homogeneity (homogeneous vs. heterogeneous) by

Sex (male vs. female) ANOVAs.

The RT and percent error results are shown in Table 1, collapsed over sex. In the RT analysis the only significant factor was that of homogeneity, with homogneous displays producing faster responses overall ($F[1,18]= 9.30$, $P < .01$). The task factor produced a marginally significant effect ($F[2,18]= 2.97$, $p <$ .10), but there was no significant interaction between these variables ($F[2,18]=$ 2.37).

In the error analysis, there was again a significant effect of Homogeneity ($F[1,18]= 7.66$, $p = .01$), but also an interaction between Task and Homogeneity ($F[2,18]= 11.17$, $p = .001$). A decomposition of the interaction showed that the advantage of heterogenous displays in the "both" task was significant ($p < .05$), as was the homogeneous advantage in the "or" task ($p < .001$). The "add" task effect was marginally significant ($p < .10$).

<u>Redundancy effects</u>

Post-hoc consideration was given to the possibility that redundancy in the numerical indicators had varying effects depending on the type of display shown. By chance, the "both" task used a stimulus pair set which was evenly split between redundant pairs (e.g., "7,8", both indicators requiring a yes response, and "1,3", both requiring a no response), and nonredundant pairs (e.g., "2,5", requiring both no and yes responses). Redundancy in this instance refers to duplication in the two required responses, even though the task formally required separate processing of the indicators.

Redundancy effects were assessed by calculating median RTs and percent errors for nonredundant and redundant pairs and subjecting them to Redundancy by Homogeneity ANOVAs. Table 2 shows the results. In the RT analysis, Redundancy showed both a main effect ($F[1,7]= 18.06$, $p < .01$) and an interaction with Homogeneity ($F[1,7]= 12.32$, $p = .01$). Clearly, heterogeneous displays showed a larger redundancy advantage than did homogeneous displays. Reinforcing these

Table 1. RT (percent error) results of Experiment 1.

	Task					
	Both		Add		Or	
Heterogeneous	691 msec	(6.4%)	689	(10.0)	559	(9.9)
Homogeneous	660	(7.4)	687	(8.8)	544	(7.7)
difference =	+31 msec	(-1.0%)	+2	(+1.2)	+15	(+2.2)

Table 2. RT (percent error) redundancy effects in the "Both" task of Experiment 1.

	Pair					
	Nonredundant		Redundant		Difference	
Heterogeneous	714 msec	(7.7%)	674	(5.0)	+40 msec	(+2.7%)
Homogeneous	671	(8.1)	653	(6.9)	+18	(+1.2)

effects, the error analysis produced similar results ($F[1,7]= 5.81$ and 7.90, both $p < .05$). These analyses were not possible for the "add" and "or" tasks, because redundancy is meaningless for the former, and the stimulus pairs for the latter by chance incorporated an almost perfect confounding between the presence or absence of redundancy and whether a no or yes response was required.

Hemispheric effects

Finally, some consideration was given to possible hemispheric differences in processing bargraph and word indicators. In fact, words rather than digits were chosen as the verbal indicators to make this analysis more appropriate in hemispheric terms, since in general, studies involving recognition of lateralized word stimuli produce reliable visual field asymmetry (e.g., Barry, 1981; Boles, 1983; Boles, 1984; Hellige, Zatkin, & Wong, 1981), while single digits are rarely if ever used as lateralized visual stimuli and so are not well validated (as contrasted with multiple digits; see Hatta & Dimond, 1980; Yeni-Komshian, Isenberg, & Goldberg, 1975). Analysis of the data centered on the two heterogeneous conditions, in which the left and right field stimuli were variously bargraph-word and word-bargraph. Under the assumption that bargraph interpretation (presumably requiring spatial processing) involves right hemisphere processes, while words involve left hemisphere processes, faster and more accurate responses would be expected for the bargraph-word arrangement than for the reverse. However, analyses using RTs and errors (adjusted as described above for sequence effects) did not support this assumption. Thus in a RT analysis using the factors of Task ("add" vs. "or", the "both" task omitted since display type was confounded with an individual's response order), Display (bargraph-word vs. word-bargraph), Hand of response (left vs. right), and Sex (male vs. female), Display was not a significant factor ($F < 1$). Nor was it significant in an analogous ANOVA using percent errors ($F[1,8]= 2.63$). Inspection of the means showed that bargraph-word displays were responded to faster than word-bargraph displays by 6 msec (621 vs. 627 msec), but that the error data were in the opposite direction (10.0 vs. 9.3%). The only significant laterality effect in the two analyses was that of Hand in RT, right hand responses producing substantially faster RTs than left hand responses (567 vs. 681 msec; $F[1,8] = 5.89$, $p < .05$).

Bargraphs vs. words

It should be noted that in all three tasks, bargraph-bargraph displays were responded to much faster than word-word displays, the mean RT difference being 145, 78, and 116 msec for the "both", "add", and "or" tasks respectively ($t[7]$ = 11.27, 3.44, and 9.23; all $p < .02$). While this outcome is consistent with the notion that numeric information is best accessed through spatial/analog rather than verbal/digital means, it should be interpreted cautiously since the words were presented in an unfamiliar vertical orientation, and the bargraphs had a comparison indicator placed exactly at the criterion ("five") level. In addition, other characteristics of the displays such as size and letter font might be expected to influence RT. If these parameters had been set differently, the results might have been different.

Discussion

Of primary interest in Experiment 1 were the homogeneity/heterogeneity comparisons across the three tasks. According to the view that integration of information places a premium on homogeneous displays, while separate processing emphasizes heterogeneous displays, the "add" and "or" tasks should have resulted in a homogeneous display advantage, while the "both" task should have produced a heterogeneous advantage. The results, however, were ambiguous with respect to this prediction. While such a pattern did emerge in errrors, no such results were found in the RT data. In addition, the RT trends were such that the error results might be attributable to speed-accuracy tradeoff, as comparison of the

RT and error results for the "both" task in Table 1 suggests. Heterogeneous displays produced more accurate but slower responses.

Perhaps the most encouraging result of the experiment came from assessment of redundancy effects in the "both" task. As shown in Table 2, redundant displays produced faster RTs than nonredundant displays, and the effect was larger for heterogeneous than for homogeneous displays. This would be expected if there is more parallel processing of heterogeneous displays relative to homogeneous displays: that is, if a bargraph and a word are processed in parallel during preparation for the first response, there is opportunity for cross-talk to influence response time. Conversely, if there is less parallel processing of homogeneous displays, there is less opportunity for cross-talk and so a smaller redundancy effect. These results support multiple resource theory, since displays exploiting multiple resources produced a greater redundancy effect.

The hemispheric contrasts produced unexpected results. When bargraph-word and word-bargraph configurations were compared, there was little difference either RT or errors. There was, however, a main effect of response hand, right hand responders being 86 msec faster than left hand responders. Such a result is intriguing since in RT experiments using otherwise unlateralized processes, hand differences are negligible (typically under 10 msec) even though right-handed subjects are used (Bisiach, Mini, Sterzi, & Vallar, 1982; Milner & Lines, 1982). This indicates that the effect can not be attributed to hand preference alone. One possibility is that interpretation of the two display types involved processes lateralized to the same hemisphere, so that the visual field arrangement made little difference (one indicator was always projected to the "wrong" hemisphere). Yet the hand used in making the response was important by virtue of the unilateral connections of hemisphere to hand. It should be emphasized, however, that 86 msec is far above the consensual upper limit of interhemispheric transmission time (Bashore, 1981; Milner & Lines, 1982), suggesting that even if the "same hemisphere" explanation is valid, it is not the entire story.

In any case, the observed effects of redundancy when combined with an informal observation made by the experimenter, led to a second experiment designed to produce a larger Task by Homogeneity interaction. The observation made during practice blocks (the only time the experimenter stayed in the room with the subject) was that instead of making two independent responses in the "both" task as formally required, subjects often emitted the responses in rapid succession, seemingly as a single prepared response pattern. In effect, subjects may not have achieved much independence between the two successive responses to a display on these trials. If so, this would work against the Task by Homogeneity interaction, because in practice (as opposed to formal requirements) subjects would be treating the "both" task as an integration task on some proportion of trials.

In response to this observation, the "both" task was redesigned to encourage greater independence between the two responses. The first response was kept the same, a five-or-more vs. less-than-five two-choice keypress. The second response, however, was changed so that (1) the decision was an odd/even discrimination, (2) the response was a go-no-go keypress, and (3) the keypress was made with the foot opposite the hand of first response. It was hoped that by thus making the decision, the response choice, and the limb of output different between the two responses, greater *de facto* independence would be achieved.

EXPERIMENT 2

Method

With very few exceptions, the method was identical to that of Experiment 1. First, the "both" task employed one hand-operated keyboard for the first response, and a second keyboard that could be operated by the opposite foot for the second response. Although the same stimulus pairs were used, the second response involved an odd-even judgment: if the indicator had displayed an odd number, the subject was to press the footswitch. Otherwise the computer waited until the response deadline and then continued to the next trial. It was recognized that the odd-even judgment would be difficult for bargraphs and would lead to a high error rate. However, since it is the first and not second response which is of primary concern, this was considered acceptable.

Because of the necessity of waiting through deadlines on about half the trials, the "both" task went much slower in this experiment. Accordingly, for all three tasks the session was shortened to one practice and two experimental blocks for each of the four display conditions. In other words, the reversed ordering of conditions run in Experiment 1 was not used here, resulting in half the data per subject. Eight new subjects, the samples balanced by sex, were run in each of the three tasks.

Results

Once again, median RTs and percent errors were corrected for sequence effects, collapsed into homogenenous vs. heterogeneous displays, and subjected to three-factor ANOVAs.

The RT and error results appear in Table 3. Clearly the Task by Homogeneity interaction in RT was much larger than that in Experiment 1 ($F[2,18]= 9.34$, $p = .002$). Decomposition showed a significant heterogeneous advantage for the "both" task ($p < .01$) and a significant homogeneous advantage for the "or" task ($p < .01$), but no significant difference for the "add" task. Besides the interaction,

Table 3. RT (percent error) results of Experiment 2.

	Task					
	Both		Add		Or	
Heterogeneous	737 msec	(4.9%)	820	(8.0)	666	(4.4)
Homogeneous	827	(3.5)	824	(6.5)	619	(4.5)
difference =	-90 msec	(+1.4%)	-4	(+1.5)	+47	(-0.1)

there were also main effects of Task ($F[2,18]= 3.89$, $p< .05$) and Sex ($F[1,18]= 5.40$, $p < .05$). Males responded 128 msec faster than females (685 vs. 813 msec). There were no significant effects in the error analysis.

<u>Redundancy effects</u>

Redundancy effects were again analyzed for the "both" task, although "redundancy" in this case is an abstraction: as adopted in Experiment 1, it refers to whether both indicators were of numbers either five-or-more, or less-than-five, even though the second response was an odd-even discrimination. Analysis proceeded similarly to the first experiment, with Table 4 showing the results.

The RT results once again showed a Redundancy by Homogeneity interaction ($F[1,7]= 9.45$, $p < .02$). Decomposition revealed a significant effect for heterogeneous displays ($p < .01$) but no effect for homogeneous displays. In the error analysis the interaction was marginally significant ($F[1,7]= 3.48$, $p = .10$) and as Table 4 shows, it was of similar form to the RT results.

<u>Hemispheric effects</u>

As for Experiment 1, bargraph-word and word-bargraph displays were compared in four-factor ANOVAs for the "add" and "or" tasks. Display arrangement was not a significant factor in the RT analysis ($F < 1$), the bargraph-word displays producing only an 8 msec advantage in RT over word-bargraph displays (739 vs. 747 msec). The only term in which a laterality variable was significant was the Display by Hand by Sex interaction ($F[1,8]= 9.06$, $p < .02$), but inspection did not suggest an interpretation, and since the interaction did not appear in Experiment 1 it will not be discussed further. The Hand of response factor, it should be noted, was not significant in this experiment in spite of a substantial trend favoring the right over the left hand (709 vs. 777 msec; $F[1,8]= 1.04$).

The error analysis likewise failed to show a significant main effect of

Table 4. RT (percent error) redundancy effects in the "Both" task of Experiment 2.

	Pair					
	Nonredundant		Redundant		Difference	
Heterogeneous	766 msec	(5.4%)	718	(3.5)	+48 msec	(+1.9%)
Homogeneous	820	(3.1)	837	(4.2)	-17	(-1.1)

Display, the bargraph-word arrangement producing slightly more errors than its reverse (6.0 vs. 5.7%; $F < 1$). The only significant laterality effect was an interaction of Display with Hand ($F[1,8] = 5.26$, $p = .05$). Bargraph-word displays produced fewer errors than word-bargraph displays when the left hand responded (3.9 vs. 5.9%), while the opposite was true when the right hand responded (8.0 vs. 5.5%).

Discussion

An attempt to force a larger Task by Homogeneity interaction in Experiment 2 was quite successful. Apparently some combination of the various changes to the "both" task encouraged greater independence in the processing of the two indicators, producing a substantial advantage for heterogeneous compared to homogeneous displays. This is in sharp contrast to the "add" and "or" tasks, in which the results essentially replicated those of Experiment 1. The "or" task produced a fairly large homogeneous display advantage in RT, while the "add" task produced little difference. The implications of these results, and of the other subsidiary findings, are explored in the general discussion below.

General Discussion

The major findings of the two experiments can be summarized as follows. First, a task configuration requiring separate processing of two information sources produced an advantage for heterogeneous over homogeneous displays. This was demonstrated most clearly in Experiment 2, in which steps were taken to ensure that the sources were independently processed rather than combined into a single response pattern. Second, requiring that the sources be integrated before response (as in the "add" and "or" tasks) eliminated this advantage. In fact, for the task designed to implement response integration (the "or" task), the advantage actually reversed and favored homogeneous rather than heterogeneous displays. Third, the nonintegration task produced an interesting redundancy effect in which heterogeneous displays showed redundancy gain while (with some apparent variability over experiments) homogeneous displays did not. Finally, while it made little difference whether heterogeneous displays were arranged in the order bargraph-word or word-bargraph, a large right hand response advantage was obtained which was significant in one experiment and present as a trend in the other.

Turning first to the observation that the nonintegration "both" task resulted in a heterogeneous display advantage, it can be noted that this finding is analogous to previous dual-task results from this laboratory, and serves as additional support for multiple resource theory (Wickens, 1980, 1984). According to that theory, "time-sharing" between tasks is most effective when nonoverlapping mental resources are required in processing the tasks. In the second experiment, the two tasks were designed to require different decision processes (magnitude vs. odd-even judgments), different alternatives for response (two-choice vs. go-no-go keypresses), and wholly different effectors (hand vs. foot responses on opposite sides of the body). In this environment, it was found that when the display indicators were also different (a bargraph and a word), responses were faster than when they were the same (both bargraphs or both words). This is consistent with the advantage expected from the use of nonoverlapping resources, and it contrasts with the results from the "both" task of Experiment 1. In that experiment, the two tasks required the same decision processes, the same response alternatives, and analogous effectors (the two hands), and the advantage in accuracy obtained by heterogeneous displays was balanced by a disadvantage in latency. The probable interpretation is that subjects sometimes treated the task in this experiment as an integration task, regardless of its formal requirement of independent responses. The informal observation that subjects seemed to produce single prepared response patterns (even though with both hands) is consistent with the interpretation.

The greater heterogeneous advantage of the "both" task in Experiment 2, relative to Experiment 1, has at least one parallel in the experimental literature. Chernikoff and Lemay (1963) compared performance when subjects tracked two independent axes both having the same dynamics (which is analogous to the "both" task of Experiment 1), with performance when the two tasks had different dynamics and thus different internal control laws (analogous to the "both" task of Experiment 2). They found that the effect of using two separate controls versus one integrated XY control to track the two axes, depended on whether the same or different dynamics were used. When heterogeneous dynamics were tracked, control separation improved performance (analogous to the findings of Experiment 2). When common dynamics were used, control separation detracted from performance. These findings, along with the results reported here, define a sort of "compatibility of separation". That is, if some processing stage or stages benefit from greater separation, then performance will be improved if other stages have greater separation as well.

An issue heretofore unaddressed by multiple resource theory,and one of central interest here is whether tasks requiring integration of information sources continue to benefit from the use of nonoverlapping resources. From our results it would appear not. Neither integration task ("add" and "or") produced an advantage favoring heterogeneous displays, and for the "or" task the opposite was in fact found. At minimum these results imply a constraint on the application of multiple resource theory, suggesting that as opposed to the situation for which it was originally intended (the time-sharing of multiple tasks), the theory may not always be applicable when the integration of display indicators is required within a single task. Somewhat surprisingly, the advantage to common format is most pronounced when the indicators to be integrated can be processed separately right up to the point of response processes (the "or" task), rather than when the indicators are to be integrated during in central processing operations (the "add" tasks). A possible explanation of this is that central processing limitations in the "add" task impose a more serial mode of processing in which indicator estimations are made serially and then combined. Under these circumstances it would then make relatively little difference whether the indicators were in the same or different formats. By contrast, the "or" task may allow a more parallel mode of processing in which there is a benefit to the mental use of a single magnitude judgment algorithm (that used either for bargraphs or for words) and through which both indicators can be processed more-or-less simultaneously. Although we have no hard evidence to support this interpretation, it does agree with the introspections of the first author, who was a pilot subject in the study.

This interpretation has an interesting ramification. Specifically, it suggests that the homogeneous display advantage enjoyed by integration tasks should be limited to instances where the processing load is light enough for the indicators to be processed in parallel. In some cases, if processing load is increased, a point should be reached where the carrying capacity of the parallel process is exceeded. Under these conditions the multiple resource model should again become applicable, and the advantage of homogeneous displays should decrease, disappear, and then reverse as load increases. We are currently testing this possibility. If found to be true, it would mean that the constraint on multiple resource theory implied by the integration findings would itself be constrained to instances of information load below the carrying capacity of parallel channels.

Pending the results of load manipulations, however, a second possible interpretation of the "add" task outcome should be mentioned. That is, the reason a homogeneous advantage was not found may be that strategy covaried with display type. Again based on the first author's introspections, it seemed as if word-word displays called on a verbal strategy of addition (e.g., "one plus six equal seven"), bargraph-bargraph displays called on a spatial strategy (in which one bargraph was mentally "stacked" on top of the other and compared to the top reference line), and mixed displays called on a verbal-to-spatial transformation followed by a spatial strategy (i.e, the word was mentally transformed to something like a bar, which was then stacked on top of the bargraph). Given heterogeneity of strategy across display types, any outcome is possible depending on the latencies of various strategic components. In this case, it could well be that the average latency of the homogeneous display strategies was roughly equal to that for the heterogeneous display strategy, producing no RT difference.

By this competing account, one of the critical determinants in the design of an optimal display is the strategy that will be used in extracting information from it. The problem should be most acute when information is to be integrated at a central cognitive level, where different strategies can yield equivalent outcomes. It should be much less a problem when information is to be combined at the response level, since by that point, central processing and its attendant strategies would already have taken place. Thus in the "or" task used here, although different processes were doubtless involved in the magnitude estimation of bargraph and word indicators, there is no reason to believe that these processes differed as a function of display type: i.e., a bargraph (or word) was processed in the same manner regardless of the nature of the accompanying indicator. Again, this agrees with introspections made while performing the task.

Turning to the redundancy gain findings, the fact that redundancy gain was found in the "both" task with heterogeneous displays but not with homogeneous displays, appears to be an observation consistent with multiple resource theory. That is, if as suggested above, heterogeneous displays allow more time-sharing and thus more parallel processing of the two indicators, there should be greater opportunity for cross-talk allowing the magnitude of one to influence a decision about the other. When both numbers are high, or both are low, faster RTs would result than when the magnitudes oppose one another. In contrast, homogeneous displays produce less efficient time-sharing and (presumably) relatively more serial processing of the indicators. Under these circumstances, there is less opportunity for cross-talk resulting in less redundancy gain. In fact, the homogeneous displays of the two experiments combined produced little evidence of <u>any</u> gain, the observed gains of +18 and -17 msec offsetting and differing nonsignificantly from one another ($F[1,14]= 1.77$).

The increase in redundancy gain brought about by parallel processing has some precedent in visual perception. Francolini and Egeth (1980) and Kahneman and Henick (1981; as cited by Kahneman and Chajczyk, 1983) have reported that redundancy gain <u>and</u> response conflict in a Stroop-like task are both enhanced to the extent that the target stimulus and the distractor (e.g., color ink and a color word) belong to the same object, a condition argued to foster parallel processing. In effect, parallel processing was encouraged by reducing spatial distance. In the current investigation it was encouraged by increasing distance in the resource space.

Finally, we have little to add to our interpretation of the right hand superiority in RT (86 msec large) discussed after Experiment 1, except to point out that a similar trend was seen in Experiment 2 (68 msec). These figures do not differ statistically from one another, and an assessment of their combined significance using the "Stouffer method" of meta-analysis (Rosenthal, 1978) does yield a significant result ($z = 2.13$, $p < .05$). This very large laterality effect warrants further investigation since as pointed out earlier, it is difficult to attribute it to simple hand preference. Unfortunately, there is no easy way to infer hemispheric differences from hand differences, because a superiority of one hand in RT can variously reflect faster processing by the opposite hemisphere (Moscovitch, Scullion, & Christie, 1976), or an interference effect between processing stages with the ipsilateral hemisphere actually being faster during earlier stages (Green, 1977; Green & Well, 1977).

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