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Circle size and diameter tilt: A new look at integrality and separability

BONNIE C. POTTS
Mindtalk Consulting, Dallas, Texas

ROBERT D. MELARA
Purdue University, West Lafayette, Indiana

and

LAWRENCE E. MARKS
John B. Pierce Laboratory, New Haven, Connecticut
and Yale University, New Haven, Connecticut

In six experiments using the speeded classification paradigm, we provide evidence that the ostensibly "separable" dimensions of size and orientation can produce patterns of either separability or asymmetric configurality, depending on the spatial arrangement of the stimuli. In all experiments, subjects classified large or small circles containing a single line in one of two possible orientations. When the line touched the circle's perimeter, thereby defining the diameter of the circle (Experiments 1–4), asymmetric configurality obtained: Variations in size interfered with classification by orientation, but variations in orientation did not interfere with classification by size, and redundancy gain was weak or absent. When the lines fell completely within (i.e., did not touch) the circles (Experiments 5 and 6), the results were consistent with separability: There was neither redundancy gain nor interference. Taken together, the results add to the growing body of evidence that classification of specific dimensional pairs as separable or integral may be less feasible than identifying the more general conditions that increase or decrease the psychological salience of dimensional structures and facilitate or interfere with selection of optimal processing strategies.

Since its inception, the study of multidimensional processing has sought to distinguish stimulus dimensions that unavoidably interact from those that do not. To describe this distinction, Garner (1970) defined "separable" dimensions as ones that can be selectively attended; they show neither facilitation when correlated nor interference when varied orthogonally in speeded classification tasks. On the other hand, "integral" dimensions produce a failure of selective attention in such tasks; thus, performance benefits from correlation and is hampered by orthogonal variation (*Garner interference*, GI). Note that "interaction" denotes a general conception of any influence of one dimension upon another. Thus, we define integrality as a particular type of interaction.

Generalizing about the interaction of dimensions across specific stimuli and experimental conditions has been difficult. Whether in speeded classification or similarity rating tasks, few pairs of dimensions have shown themselves unambiguously to be either interacting or not. Imai and Garner (1965), Felfoldy and Garner (1971), and L. M. Ward (1982) showed that task demands and specific instructions can alter the extent to which dimensions interact. Pomerantz and Garner (1973) and Lockhead and King (1977), among others, have shown patterns of interaction that fail to conform to criteria for either integrality or separability. Even the validity of the criteria themselves has been disputed (e.g., Ashby & Maddox, 1994; Townsend & Thomas, 1993). Several investigators have documented developmental differences in the ability to extract dimensional structure (e.g., Kemler & L. B. Smith, 1979; Shepp, 1978; L. B. Smith & Evans, 1989; L. B. Smith & Kemler, 1978). There is also some support for individual differences in the extent to which people process stimuli by overall similarity or dimension by dimension (J. D. Smith & Baron, 1981; T. B. Ward, 1985). Finally, Pomerantz and his colleagues (e.g., Pomerantz, Pristach, & Carson, 1989; Pomerantz & Schwaitzberg, 1975) and others have suggested that perceptual grouping of experimenter-defined dimensions may be a voluntary strategy that perceivers use to optimize performance. Thus, there is growing evidence that a strictly dichotomous distinction between interacting and noninteracting dimensions is inappropriate.

The present study reinforces this notion by showing that even prototypically separable dimensions can interact and that the conditions that produce this interaction may generalize to other types of stimuli as well. We assert that a new language is needed to analyze perceptual inter-

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action and that the traditional distinction between integrality and separability, which emphasizes inherent relationships among the dimensions, should be replaced by models that elucidate the rules perceivers employ to transform and use multidimensional stimulus information. By shifting from structure to function—that is, to the optimal use of information—we may discover more about what perceivers actually do, and why the particular stimulus dimensions per se are not necessarily the best predictors of the type of processing (separable vs. interactive) that will occur. In short, we believe that it is more appropriate to explore the determinants of interactive processing than to attempt to establish a pairwise classification system of separable vs. interactive dimensions.

Integrality as a Prototype of Interaction

Lockhead (1966) provided a phenomenological definition of dimensional integrality: Dimensions are said to "join one another" so that it is difficult to notice one without also noticing the other. Garner (1970) gave a strictly logical, limiting definition for potential integrality: In order for one dimension to exist, a level on the other dimension must be specified. A classic example of this logical type of integrality comprises the color dimensions of value (brightness) and chroma (saturation): Brightness cannot exist without some level of saturation, and vice versa. Not only do these dimensions interact in speeded classification (e.g., Garner & Felfoldy, 1970; L. B. Smith & Kemler, 1978), but it is often difficult for unpracticed observers to extract attribute information from these dimensions at all (Foard & Kemler Nelson, 1984; but see Melara, Marks, & Potts, 1993). Yet, if the two dimensions are separated spatially, so that Garner's (1970) definition of integrality is no longer relevant to the task, no interaction occurs. Hyman and Well (1968) demonstrated this with value and chroma by providing the information about each dimension on a separate Munsell color chip, rather than on a single chip. In this case, subjects were able to attend selectively to each dimension, exhibiting no evidence that the other dimension was processed at all. Such results suggest that removing the dimensions' mutual (logical) dependence has perceptual consequences, allowing the stimuli to be processed analytically.

Consider, in this regard, the visual stimuli formed by combining a circle with its diameter (or radius), where the circle can vary in size and the diameter (radius) can vary in orientation. On the basis of Garner and Felfoldy's (1970) work with these stimuli, the dimensions of size and orientation often are cited as separable (e.g., Ashby & Maddox, 1990; Shepp, 1989). By definition, the diameter or radius of a circle provides information about its size, but the size alone provides no information about the angle of orientation of the line within it (which can be described as the *tilt* of the circle). Thus, at least logically, there is an asymmetric integrality between these two dimensions; yet, they have been purported to be separable dimensions psychologically. A closer look at previous studies and our experiments with these dimensions helps resolve this apparent paradox.

Size and orientation have shown at least weak evidence of interaction (e.g., Ashby & Lee, 1991; Garner & Felfoldy, 1970; Shepard, 1964; T. B. Ward, 1985). Shepard's (1964) subjects judged the similarity of circles varying in size and tilt of the radius. Although the resulting data did not strongly support integrality, neither did they suggest separability. Thus, there was at least a suggestion that size and tilt were not inherently separable dimensions. Garner and Felfoldy's (1970) subjects tried to attend to either circle size or diameter tilt as the other (irrelevant) dimension varied in either a correlated or orthogonal fashion. The dimensions did not interact strongly, but there was some evidence that varying size affected processing of tilt. This pattern was reproduced by Ashby and Lee (1991), using both classification and similarity tasks, and by the present authors in our first four experiments. Garner and Felfoldy considered the possibility that some integrality of length and tilt could be responsible, but they did not test this hypothesis. T. B. Ward (1985) held line length constant for various circle sizes, but he did not compare this condition with one in which line lengths vary with circle size (nor was this the purpose of his study). However, L. B. Smith and Kilroy (1979) found that length (or size) and orientation (of arrows) were neither wholly separable nor integral.

Hyman and Well (1967, 1968) also found some evidence of interaction between size of circles and inclination of radii in subjects' card sorting and similarity judgments, although the conclusion from both studies was that these dimensions are more nearly separable than integral. An underemphasized, but critical, conclusion to Hyman and Well's (1968) study was that the "continuum of combining rules" (for multidimensional stimuli) might better be approached as an issue of optimal use of information than as an indicator of some specific, stable metric of psychological space that maps onto the various physically specifiable dimensions. This view has been expressed by Townsend (e.g., Townsend & Thomas, 1993) and by Pomerantz and his colleagues (e.g., Pomerantz & Pristach, 1989; Pomerantz et al., 1989), who emphasized the important distinction between GI as a failure of selective attention versus a switching of attention to dimensions not specified by the experimenter. Ashby and Maddox (1990) made a similar point; however, unlike Pomerantz et al., they proposed that this switching of attention is not under conscious control but occurs automatically as the perceiver strives for optimal performance.

Our study provides empirical support for the notion that the dimensions of circle size and tilt interact under some circumstances but are completely separable under others. More importantly, we are able to make some more general assertions as to what constitute "appropriate circumstances" that predispose one to perceive stimulus dimensions as primarily separable or interactive.

Perceptual Versus Decisional Integrality

Ashby and colleagues (e.g., Ashby & Maddox, 1994; Ashby & Townsend, 1986) distinguished between perceptual and decisional integrality. In this view, perceptually integral dimensions are bound together psychologically in the earliest stages of processing and remain so; thus, they should show GI. With decisional integrality, the dimensions may be processed separately at some relatively early stage, but the outputs of the processed dimensions interact at a decisional stage, before the subject responds; thus, these dimensions would also produce GI, but for a different reason. Pursuing this line of thought, Ashby and colleagues contend that any past evidence of interaction of size and orientation in speeded classification tasks may have been due to the inherent methodological bias of such tasks toward finding integrality. As our Experiments 5 and 6 will show, however, size and orientation can produce a pattern of results that is clearly consistent with separability, despite this bias.

Ashby and Maddox (1994) have proposed a test for *marginal response time (RT) invariance* as a more appropriate indicator of the existence and type of dimensional interaction than the difference between mean performance in the baseline and filtering conditions. The criterion for separability in this case is that, in the filtering task, the RTs for a single level of a relevant dimension are invariant, despite the level of the irrelevant dimension. Using this test in addition to the more traditional measures of GI and redundancy gains may allow one to make finer distinctions among, for example, perceptual and decisional integrality or separability versus separability with context effects.

A Continuum of Separability?

Many have advocated the concept of a continuum of integrality–separability (e.g., Foard & Kemler Nelson, 1984; Garner, 1974; Hyman & Well, 1968; Shepp, 1989; L. B. Smith & Kemler, 1978). An advantage of this view is that it, like Ashby and Maddox's (1994) proposed classification system, avoids the rigid assumption that interaction is all or none. Instead, it allows for the abundant data showing various degrees and symmetry of interaction. Unfortunately, the continuum view also has a serious shortcoming (Melara & Marks, 1990): There is no evidence to show that the inconsistencies in patterns of interaction are merely quantitative (as presumed by a continuum) and not qualitative. In the quantitative view, the level of interaction is generally defined as the amount of cross talk between processing channels of the two dimensions. Cross talk, in turn, is operationalized as the amount of GI in selective attention tasks. As such, the notion of a continuum has no predictive validity; in fact, it does little more than restate the data, positioning each pair of dimensions relative to the others according to the amount of inferred cross talk. Even this approach has met with only limited success, because we have seen that the very dimensions that show strong evidence of interaction in one experimental situation can appear separable in another.

Shepp (1989) advocates the use of three labels along the continuum of dimensional interaction: integral, separable, and (spatially) separate. Integral and separable dimensions are characterized essentially as we have used the terms here. "Separateness" is exemplified by Hyman and Well's (1968) stimuli, where the dimensions are completely separated spatially by being placed on two separate chips; however, "separate" also subsumes stimuli, such as circle-and-radius or circle-and-diameter. In Shepp's (1989) view, separate dimensions flank the separable pole of the continuum of interaction. A prediction, then, is that whenever dimensions can be separated in physical space, the likelihood of their being processed psychologically as separate dimensions is increased. Although this view seems to hold well with some of the dimensions to which it has been applied, it may need refinement for two reasons. First, there is certainly much greater separation in Hyman and Well's (1968) color stimuli than in Garner and Felfoldy's (1970) circle stimuli. In the first case, value and chroma do not overlap spatially at all; however, in the second, the circles (size dimension) subsume the lines (tilt dimension) completely. Second, cross-modal stimulus combinations (e.g., pitch and brightness), which are arguably separate by Shepp's (1989) definition, nevertheless show Stroop-type patterns of interaction more consistent with integrality than with separability.

To be sure, Shepp's (1989) revision of the simple integrality–separability continuum is an improvement, as it implies a rule that is superordinate to the specific dimensions. Nevertheless, in light of our experiments, which will show that the degree of spatial overlap actually determines whether these dimensions interact or are processed separately, it is clear that a single category of separateness is insufficient.

Emergent Features

Pomerantz and his colleagues (e.g., Pomerantz & Pristach, 1989; Pomerantz et al., 1989; Pomerantz, Sager, & Stoever, 1977) have approached the issue of dimensional interaction from a more attentional perspective, characterizing "configural interaction" of dimensions (after Garner, 1976) and the existence of "emergent features" as conceptually distinct from the issue of integrality versus separability. In the *emergent features* view, as it will be called, performance exhibits GI not because the dimensions in question are necessarily integral but because subjects are attending to some dimension(s) other than those defined by the experimenter. In particular, a specific spatial arrangement of dimensions may result in a new salience of some relational or configural property not present in other arrangements of the same dimensions (e.g., the left-facing and right-facing parentheses of Pomerantz & Garner, 1973). As the present study will show, the specific spatial relationship between size and tilt has a marked effect on the degree of interaction, and this may be a function of the emergence of more salient properties. Again, discovery of the rules that govern the detection and use of such emergent properties is likely to contribute more to our understanding of the perceptual system than is examination of any specific pair of dimensions.

The Present Study

Our study used speeded classification (specifically, the Garner paradigm; see Garner, 1974) to assess the interaction of size of a circle and tilt of an enclosed line passing through the center. Garner and Felfoldy (1970) had subjects sort cards according to these dimensions in three types of experimental conditions: (1) *baseline*, one dimension is held constant at one of its levels, and the other dimension is relevant to sorting; (2) *correlated*, both dimensions vary in a perfectly correlated way, and, thus, sorting may be done on the basis of either or both; (3) *orthogonal*, sorting is done on the basis of one dimension, whereas the other dimension varies randomly. We employed the same kinds of stimuli and tasks as those used by Garner and Felfoldy, but the experiments were computerized so that the task was one of speeded classification using a keypressing response rather than card sorting. We will consider Garner's (1976; see our Table 1) and Ashby and Maddox's (1994, their Table VI) schemes for interpreting the outcomes of our experiments.

In each of six experiments with size and tilt, we sought evidence for effects of the following: (1) dimensional correlation and orthogonal variation, and (2) spatial separation of the dimensions. The experiments presented here, together with the backdrop of previous research with these dimensions, show that slight alterations in the spatial relationships of the dimensions can strongly and systematically alter the pattern of interaction of size and tilt.

GENERAL METHOD

The following were common to some or all of the experiments reported here.

Subjects

The subjects in all but Experiment 5 were members of the Yale community who were paid to participate. The subjects in Experiment 5 were students at Purdue University who participated for partial course credit. Experiment 5 alone used 40, rather than 20, subjects, but this doubling in number was unintentional. All subjects were between the ages of 18 and 35 years, and all had normal or corrected-to-normal vision. Some Yale subjects participated in more than one experiment.

Stimuli and Apparatus

The stimuli were black outlines of circles on a white background, each circumscribing a single black line. The circles could be small or large in size, and the lines could tilt to the right or left of vertical (called *clockwise* or *counterclockwise*, respectively). The thickness of the circles and the lines was 1 mm. Viewing distance was approximately 60 cm. Stimuli were presented on the monitor of an Amiga 500 computer, which also recorded responses, measured RTs to the nearest millisecond, and controlled stimulus presentation and randomization.

Table 1
Patterns of Redundancy Gain and Selective Attention in the Speeded Classification Paradigm

Type of Dimensional Relationship	Observed Pattern: Redundancy Gain	Observed Pattern: Garner Interference
Integral	Yes	Yes
Configural	No	Yes
Separable	No	No
Asymmetric integral	Yes	Yes (asymmetric)
Asymmetric configural	No	Yes (asymmetric)
Ideal	Yes	No

Design and Procedure

For each of the dimensions (size and tilt), each subject performed in five tasks: two baseline discrimination tasks, one positively correlated and one negatively correlated discrimination task, and one orthogonal classification task. The tasks are described below.

Baseline 1: When size was the relevant dimension, this task required discrimination between the large and small circles, with tilt constant at the clockwise position. When tilt was relevant, the task required discrimination between clockwise and counterclockwise, with size constant (large circles only).

Baseline 2: The tasks were the same as in Baseline 1, but the irrelevant dimension was now held constant at the value not used in Baseline 1. When size was relevant, tilt was counterclockwise; when tilt was relevant, size was small.

Positively correlated discrimination[1]: Large and clockwise were perfectly correlated; small and counterclockwise were likewise correlated. In one task, size was specified as the relevant dimension, and, in the other, tilt was relevant. The dimensional correlation was not made explicit in the instructions to the subjects.

Negatively correlated discrimination: Large and counterclockwise were perfectly correlated; small and clockwise were likewise correlated. Otherwise, this task was identical to the positively correlated task.

Orthogonal classification: When size was relevant, tilt varied orthogonally. When tilt was relevant, size varied orthogonally.

The five size tasks and five tilt tasks were performed in separate blocks within the single experimental session. Half of the subjects performed the size block first; the other half performed the tilt block first. Within a block, order of tasks was determined by a Latin square. Half of the subjects used one stimulus–response mapping; for the other half, this mapping was reversed. Within each block, the order of presentation of the stimuli was random and different for each subject.

The subjects sat in front of the monitor and read the instructions, which explained that they would see one stimulus on the screen at a time and that the stimulus would be large or small (in the size block) or clockwise or counterclockwise (in the tilt block). The subjects were given the stimulus–response mapping and asked to be as speedy and accurate as possible in pressing the appropriate key on the Amiga keyboard. The relevant stimuli for a block were shown to the subjects after they had read the instructions, but before the experiment proper began. Entering a response immediately initiated the next trial, but the subjects were allowed to rest between tasks whenever necessary. Feedback was provided via the monitor after incorrect responses and whenever RT exceeded 1 sec. On these "slow" trials, the stimulus was presented again randomly in another trial within that task. Only RTs faster than 1 sec were retained as data. As a means of minimizing differential practice effects, any block of trials in which a subject did not achieve at least 90% accuracy was considered practice and was repeated immediately. Data from the first block in which the accuracy criterion was met were recorded, and then the subject proceeded to the next block of trials.

Each block consisted of 48 trials, not including the slow trials. The subject's RT and percent correct were displayed on the monitor at the end of each task. RT was the dependent variable, and accuracy was monitored to ensure against speed–accuracy tradeoffs. The entire experimental session lasted approximately 45 min.

EXPERIMENT 1

Method

Subjects. Fourteen women and 6 men participated.

Stimuli and Apparatus. The circles' diameters measured 41 mm (small) and 63 mm (large), subtending 3.9° and 6.0° of visual angle, respectively. The two levels of the tilt dimension for the diameter lines were 15° clockwise or counterclockwise.

Results and Discussion

The mean RTs according to task and dimension are shown in Figure 1. Two aspects of the data are evident immediately: Classification was performed faster by size than by tilt, and there appears to have been no effect of tilt classification by size (as seen by lack of RT differences across size tasks). An overall analysis of variance (ANOVA) confirmed that size was the faster dimension [$F(1,19) = 15.37$, $MS_e = 2539.33$, $p < .001$] and that the main effect of task was significant [$F(4,76) = 4.11$, $MS_e = 682.46$, $p < .005$; $p < .05$, using Huynh & Feldt's, 1976, correction].[2] The dimension $\times$ task interaction approached significance [$F(4,76) = 2.50$, $MS_e = 730.54$, $p = .05$].

Pairwise comparisons among the size tasks showed that there was indeed no reliable difference between performance in the five tasks (all Fs < 1). This was not true of the tilt dimension. Although performance in the baseline tasks failed to differ significantly, there was a trend toward faster responding to tilt when size was large [$F(1,76) = 2.80$, $p = .096$], albeit in only 12 of the 20 subjects. Correlating tilt and size did not help performance [$F(1,76) = 2.30$, $p > .10$, and $F < 1$, for positively and negatively correlated tasks, respectively]. Orthogonal variation of size, however, did interfere with processing tilt [$F(1,76) = 11.60$, $MS_e = 730.54$, $p < .005$].

Tests of marginal RT invariance (Ashby & Maddox, 1994) were applied to data obtained in the orthogonal condition by comparing the distributions of RTs made to each value on the relevant dimension given the two possible values on the irrelevant dimension. Thus, for example, if the responses to the small circle were the same regardless of the tilt, then small circles would show marginal RT invariance. Response distributions were compared by means of two-tailed Kolmogorov–Smirnov tests in this and all subsequent experiments. Across experiments, with a single exception that is discussed in Experiment 4, marginal RT invariance obtained for all four stimuli in the filtering condition ($Z \leq 1$, $p > .05$).

In Experiment 1, however, the pattern of RTs was asymmetric configural, in Garner's (1976) terms. Correlating the dimensions produced no facilitation, and varying the tilt dimension neither helped nor hindered performance in the size task, but varying size hurt performance in the tilt task. Perhaps the asymmetry resulted from superior discriminability for the size dimension—that is, the subjects' attention may have been drawn to this dimension not because it was dominant perceptually in any general sense but because it was more discriminable in this particular spatial arrangement.

In order to assess whether the observed interaction of size and tilt was due to differential discriminability of the two dimensions, the procedure of Experiment 1 was repeated after pilot work determined the specific stimulus values that would produce roughly equivalent RTs for baseline size and tilt tasks.

EXPERIMENT 2

Method

Subjects. Twelve women and 8 men participated. Of these, 4 had participated in Experiment 1.

Stimuli. Experiment 1 was repeated with a single change in the stimuli: The diameter lines were now oriented at 11°, rather than 15°, clockwise or counterclockwise. (On the basis of Experiment 1's faster RTs for size, we originally reasoned that either reducing the size difference or increasing the tilt difference would facilitate equation of the two dimensions' baseline tasks. This, however, was

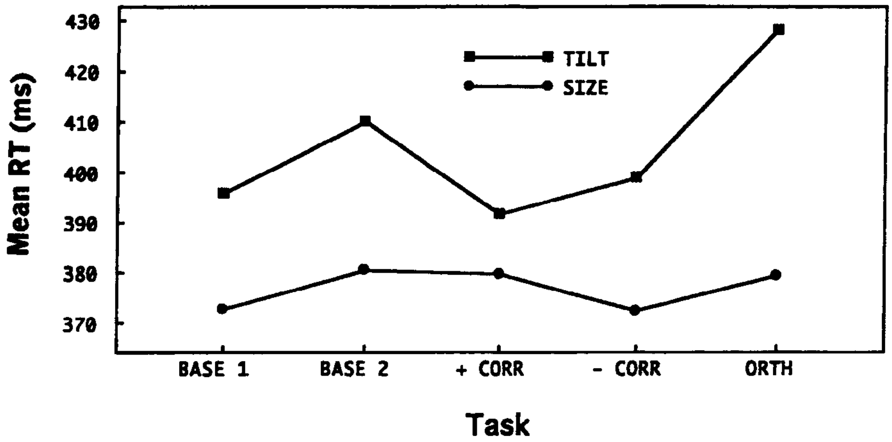


Figure 1. Mean reaction times for tilt and size dimensions as a function of task in Experiment 1. Tasks are labeled as follows: BASE 1 = Baseline Task 1: the relevant dimension varied, and the irrelevant dimension was held constant at one of its levels. BASE 2 = Baseline Task 2: the relevant dimension varied as in Task 1, but the irrelevant dimension was now held constant at its other level. + CORR = positively correlated task: size and tilt were perfectly correlated. −CORR = negatively correlated task: size and tilt were perfectly correlated in the manner not used for + CORR. ORTH = orthogonal task: the irrelevant dimension varied orthogonally to the relevant dimension.

not the case. Size remained the easier task despite decrements in size differences. Similarly, RTs for tilt did not improve with increases in angle. Only when angle of tilt was decreased slightly did RTs match those for size. We can only hypothesize that the reduction in the angle of tilt made it easier for the subjects to determine within a single fixation whether a particular segment of the diameter line was to the right or left of the vertical position.) Visual angles did not change.

Results and Discussion

The mean RTs according to task and dimension are shown in Figure 2. Whereas the pattern of results for tilt was nearly identical to that of Experiment 1, the pattern for size changed. An ANOVA confirmed that the 3-msec difference between the average of size baseline tasks (378 msec) and the average of tilt baseline tasks (381 msec) was not reliable ($F < 1$), but there was a reliable main effect of task [$F(4,76) = 9.68$, $MS_e = 715.16$, $p < .001$], indicating that size tasks were performed faster overall. There was also a reliable interaction of task and dimension [$F(4,76) = 3.19$, $MS_e = 626.98$, $p < .05$].

Although equating baseline RTs for the two dimensions appears to have had some effect on size tasks, the pattern of results for the two dimensions was still asymmetric configural (see Table 1). In the tilt tasks, the 31-msec difference between the average baseline RT (381 msec) and the orthogonal task RT (412 msec) constituted significant GI [$F(1,76) = 20.40$, $MS_e = 626.99$, $p < .001$]. In the size tasks, however, orthogonal task RTs (380 msec) differed from baseline RTs (378 msec) by only 2 msec, which was not significant ($F < 1$).

Correlating size with tilt still failed to produce reliable gain when tilt was the relevant dimension: Mean RTs to both positively and negatively correlated tasks were 369 msec; the 12-msec difference between these tasks and baseline (381 msec) did not reach significance [$F(1,76) = 2.73$, $p = .10$, for the positively correlated task; $F(1,76) = 2.87$, $p = .094$, for the negatively correlated task]. When size was relevant, the results with positively correlated stimuli mirrored those for the two correlated tilt tasks [$F(1,76) = 2.61$, $p = .11$]. For the negatively correlated task, however, there was definite benefit [$F(1,76) = 13.00$, $MS_e = 626.99$, $p < .001$].

This unusual result—redundancy gain without GI—fits the pattern for separable dimensions, but the overall outcome nevertheless resembles that of Experiment 1: An asymmetric configural relationship between size and tilt.

EXPERIMENT 3

The results of Experiments 1 and 2 differed from those of Garner and Felfoldy (1970) in one important way: There was reliable evidence of asymmetric interference of size in judgments of tilt, even when baseline discriminabilities matched. Can methodological differences account for this apparent contradiction? Many experiments have shown that card sorting need not produce qualitatively different results from other methods, yet subjects may certainly adopt different ways of approaching tasks, depending on the method used. In our experiments, the stimuli were always presented in a fixed location on the monitor. Perhaps the subjects were able to benefit from this location information differentially for each dimension. In the size tasks, they could focus their gaze on a particular region where a part of the large circle (but not the small one) appeared. Similarly, in the tilt tasks, they could focus on a part of the monitor where a particular segment of the diameter appeared whenever it was oriented clockwise or counterclockwise. In both cases, the task was reduced from discrimination to simple detection. Because more pixels were devoted to the circle than to its diameter, this strategy presumably would have been easier to implement in size tasks than in tilt tasks. In card sorting, finding the appropriate feature is more a function of eye-hand coordination than of any simple focusing strategy. We therefore determined that if such a strategy were responsible for the observed differences, the strategy should be made ineffective, and the differences eliminated, by presenting the stimuli randomly at different locations.

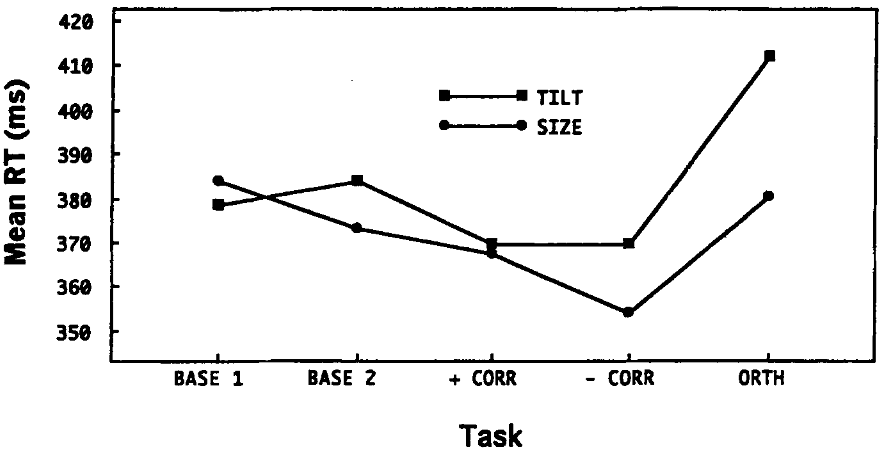


Figure 2. Mean reaction times for tilt and size dimensions as a function of task in Experiment 2.

Method

Subjects. Fifteen women and 5 men participated. Of these, 8 had participated in at least one previous experiment. Two subjects had participated in both Experiments 1 and 2; 5 subjects had participated in Experiment 1 only; and 1 subject had participated in Experiment 2 only.

Stimuli, Design, and Procedure. The experiment replicated Experiment 2 in all respects except that the stimuli were no longer centered on the monitor. Instead, each stimulus appeared randomly on each trial in one of four locations: centered at a point 3.5 cm to the upper right, upper left, lower right, or lower left of the center of the screen. No fixation point was provided; the subjects were free to fixate the stimuli wherever they appeared (and presumably did so).

Results

The mean RTs according to task and dimension are shown in Figure 3. Note the striking resemblance between these results and those of Experiment 1 (Figure 1). Adding positional uncertainty led to an RT advantage for size [$F(1,19) = 6.39$, $MS_e = 3{,}572.43$, $p < .05$], although this effect failed to reach significance in three of the five tasks [Baseline 1, $F(1,76) = 2.60$, $p = .11$; positively correlated task, $F(1,76) = 3.50$, $p = .07$; negatively correlated task, $F < 1$]. This accounts for the weak interaction of dimension × task [$F(4,76) = 2.46$, $p = .05$]. The effect of task was again reliable [$F(4,76) = 4.86$, $MS_e = 756.85$, $p < .005$ (.01)].

Positional uncertainty rendered baseline tilt judgments much more difficult when circles were small than when they were large [$F(1,76) = 9.70$, $MS_e = 784.12$, $p < .005$]; thus, averaging the baseline RTs was not appropriate. This disparity of baseline RTs made comparisons among the other tasks somewhat problematic; performance in the orthogonal condition, for example, was slower than that in Baseline 1 [$F(1,76) = 12.00$, $MS_e = 784.12$, $p = .001$], but nearly identical to that in Baseline 2 (396 vs. 391 msec, respectively) ($F < 1$). Similarly, the correlated tasks produced redundancy gain relative to Baseline 2 [$F(1,76) = 13.14$, $MS_e = 784.12$, $p < .001$], but statistically identical RTs to those of Baseline 1 ($F < 1$).

The higher RTs in Baseline 2 for the tilt dimension continued a trend seen in Experiments 1 and 2, where mean RTs in Baseline 2 were higher than in Baseline 1. Simply put, discriminating tilt was more difficult when the circles were small than when they were large. But size per se may not have been the critical variable. Large and small stimuli differed in density as well, and the subjects may have been using locations of higher density (i.e., vertices where the line met the circle) as indications of the value on the tilt dimension. If so, then this strategy was probably more effective with large circles, where density differences were more discriminable, than with small circles. In Experiment 5, we provide evidence that a very different pattern of results for tilt tasks can be produced by a simple change in the stimuli that discourages the use of this strategy.

For the size dimension, Baseline 1 and 2 RTs (387 and 394 msec, respectively) did not differ significantly ($F < 1$); therefore, again these were averaged for comparison with the other tasks. Variations in tilt produced neither gain in the correlated tasks nor interference in the orthogonal task (all Fs < 1). Thus, with the exception of slower RTs in the Baseline 2 condition, the present results again follow the pattern of asymmetric configural interactions.

EXPERIMENT 4

Experiments 1–3 converged on a single conclusion: Variations in size affect processing of tilt, but variations in tilt do not affect processing of size. In two of the three experiments, this result could reflect better discriminability of the sizes. In Experiment 4, we tested this idea directly by making tilt more discriminable than size. If size is the preferred dimension even when tilt is more discriminable, then the asymmetry found in the first three experiments is a stable characteristic of the pairing of these two dimensions. The alternative is that the concept of separable versus mandatorily interacting status for these dimensions may be overridden by the issue of discriminability.

Method

Subjects. Eleven women and 9 men participated. Of these, 7 subjects had participated in at least one previous experiment. One had

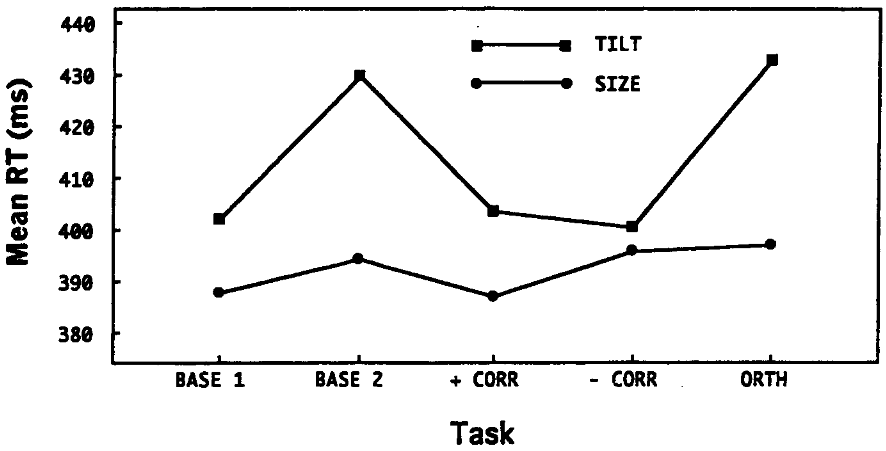


Figure 3. Mean reaction times for tilt and size dimensions as a function of task in Experiment 3.

participated in Experiments 1, 2, and 3; 2 subjects had participated in Experiments 1 and 3; the remaining 4 subjects had participated in one experiment only.

Stimuli, Design, and Procedure. The experiment replicated Experiment 3 in all respects except that the small circles now measured 45 mm and the large circles 55 mm in diameter (4.3° and 5.25°; still within the range of visual angles used in Experiments 1–3).

Results

The mean RTs according to task and dimension are shown in Figure 4. It is obvious that, in this case, tilt had the RT advantage over size. The overall ANOVA confirmed this [$F(1,19) = 7.90$, $MS_e = 3{,}597.93$, $p = .01$]. The effect of tasks did not reach significance [$F(4,76) = 2.07$, $p = .093$], but the dimension × task interaction did [$F(4,76) = 3.32$, $MS_e = 658.81$, $p = .015$ ($< .05$)]. Contrasts showed that there was a reliable difference in performance between the two dimensions in all but the positively correlated and orthogonal tasks.

Processing size now benefited from positive correlation with tilt [$F(1,76) = 8.02$, $MS_e = 658.81$, $p < .01$], relative to the two baseline RTs, which did not differ ($F < 1$). There was neither benefit nor cost associated with negative correlation or orthogonal variation (Fs < 1). Marginal RT invariance held in three of the four orthogonal tasks ($Z < 1$, $p > .05$). The exception was when tilt was relevant and in the counterclockwise position ($Z = 1.42$, $p < .05$). In this task, the subjects responded faster to small circles than to large ones (387 vs. 435 msec, respectively). As previously noted, this was the only comparison in all six experiments that failed to show marginal RT invariance.

Despite the decreased discriminability of size, the subjects still found it more difficult to process tilt when size was small than when it was large; within the tilt dimension, Baseline 2 performance was again slower than Baseline 1 [$F(1,76) = 5.92$, $p = .02$]. Negative correlation produced no benefit relative to either baseline condition [$F(1,76) = 1.46$, $p = .23$, for the Baseline 1 comparison; $F(1,76) = 1.50$, $p = .22$, for the Baseline 2 comparison]. Positive correlation produced marginal gain relative to Baseline 1 [$F(1,76) = 3.65$, $p = .06$] and no gain relative to Baseline 2 ($F < 1$). Likewise, orthogonal variation interfered with performance relative to Baseline 1 [$F(1,76) = 10.60$, $MS_e = 658.81$, $p < .005$] but did not affect performance relative to Baseline 2 ($F < 1$).

It is clear that changes in relative discriminability weakened the pattern of asymmetric interaction observed in the previous experiments, yet the results still conform more closely to the asymmetric configural pattern than to any other. Interestingly, making tilt more discriminable than size did not reverse the direction of the asymmetry. This suggests that the perceptual system's apparent preference for one dimension over another can reflect more than a preference for superior discriminability.

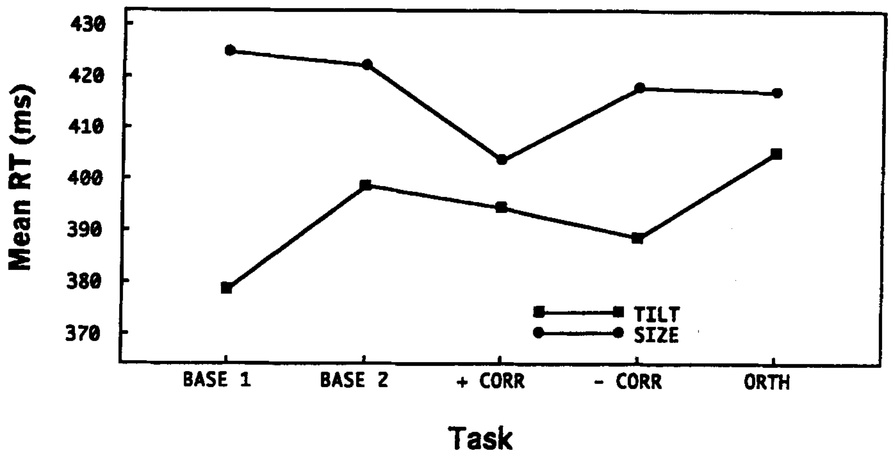
EXPERIMENT 5

Perhaps a poorly discriminable dimension influences processing of more discriminable dimensions when the pair conforms to Garner's (1970) early definition of integrality: A pair of dimensions is integral if each needs the other to exist. As mentioned earlier, in our and Garner and Felfoldy's (1970) stimuli, the diameter line is, by definition, an indicator of the circle's size, but the circle's size provides no information about the tilt of the line. Thus, removing their intrinsic asymmetry may alter the pattern of interaction between them. Experiment 5 posed a preliminary test of this idea by removing size information from the lines.

Method

Subjects. Twenty-two women and 18 men participated.

Stimuli, Design, and Procedure. Experiment 5 replicated Experiment 4 in all respects except that the length of the tilted line was fixed at 32 mm; thus, the line no longer extended through the full diameter of either the 45-mm (small) circle or the 55-mm (large) circle. This change served to remove the correlation between circle size and diameter length; thus, tilt no longer carried incidental information about size.



Task

Figure 4. Mean reaction times for tilt and size dimensions as a function of task in Experiment 4.

Results and Discussion

It is apparent from Figure 5 that performance on the tilt dimension retained its superiority, as in Experiment 4. This effect was significant [$F(1,39) = 5.62$, $MS_e = 6{,}187.89$, $p < .05$]. The most striking result, however, is the lack of RT differences as a function of task within each dimension. The overall ANOVA confirmed a complete absence of any task effect ($F < 1$), as well as any dimension × task interaction [$F(4,156) = 1.27$, $p = .28$]. It is clear that GI is absent in the orthogonal task.

Why did altering the stimuli in Experiment 5 eliminate GI in the tilt task? By removing the correlation between circle size and line length, we also removed the junctures between the circle's perimeter and the ends of the line. If the junctures served as critical (emergent) properties, or if they contributed to the emergence of configurality, this may have been responsible for the dimensional interactions observed in our study as well as previous studies. Perhaps the junctures serve to fuse the orientation and size dimensions psychologically, as well as physically.

Garner and Felfoldy (1970, Experiment 4) referred briefly to this possibility as an explanation for the facilitation of tilt processing in the correlated conditions, but dismissed it because it could not account for the asymmetric nature of the facilitation (no benefit from correlation when size was relevant). In any event, we wished to decouple the correspondence between the logical or informational connection (size/diameter correlation) and the spatial connection (juncture of diameter and perimeter). Experiment 6 accomplished this by reinstating the correlation between size and length while still omitting the junctures.

EXPERIMENT 6

Method

Subjects. Ten men and 10 women participated. Of these, only 1 subject had participated previously, in Experiments 2 and 3.

Stimuli, Design, and Procedure. Experiment 6 replicated Experiment 5 in all respects except that all lines were drawn with a 3.0-mm gap between their ends and the circle's perimeter; thus, the lines measured 39 mm (in the 45-mm small circle) and 49 mm (in the 55-mm large circle).

Results

The mean RTs according to task and dimension are shown in Figure 6. As visual inspection of the figure suggests, there were no reliable main effects nor any interaction of task with dimension (all Fs < 1). As in Experiment 5, neither redundancy gain (in the correlated tasks) nor GI (in the orthogonal task) occurred. Thus, correlation of size and line length did not by itself lead to the asymmetric interactions observed in Experiments 1–4.

SUMMARY OF RESULTS

We have demonstrated strong evidence of asymmetric interaction of the dimensions of circle size and tilt of an enclosed line, with variations in size interfering with classifications by tilt whenever the line extends to the circle's perimeter. This interference persists despite changes in the relative discriminabilities of size and tilt, and regardless of whether size and line length are correlated; however, it disappears when the juncture between the circle and the line is removed. Conversely, variations in tilt did not interfere with classifications by size in any of the experiments, and marginal RT invariance held in nearly every instance. In Garner's (1976) terms, the dimensional relationship that obtained was asymmetric configural in Experiments 1–4, where diameter lines were used, and separable in Experiments 5 and 6, where shorter, noncontiguous lines were used.

We will center our discussion on the factors that enabled alteration of the pattern from asymmetric integrality to complete separability.

GENERAL DISCUSSION

Most studies of dimensional interaction implicitly assume that there is something inherent in the dimensions or their mere combination that either facilitates or hampers

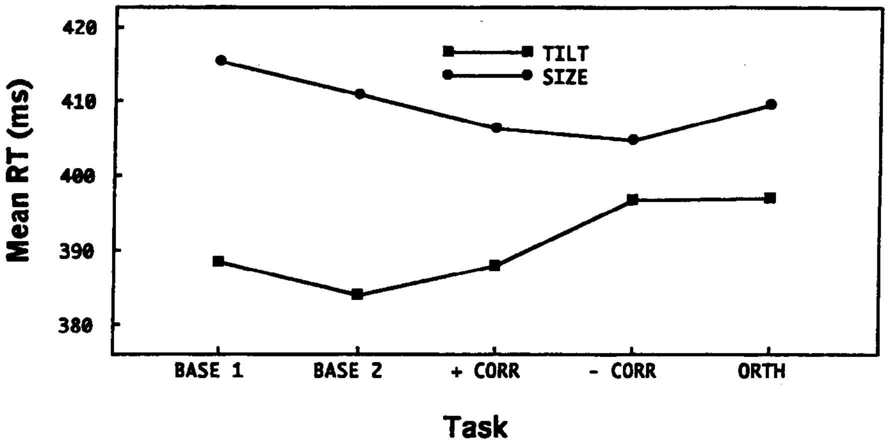


Figure 5. Mean reaction times for tilt and size dimensions as a function of task in Experiment 5.

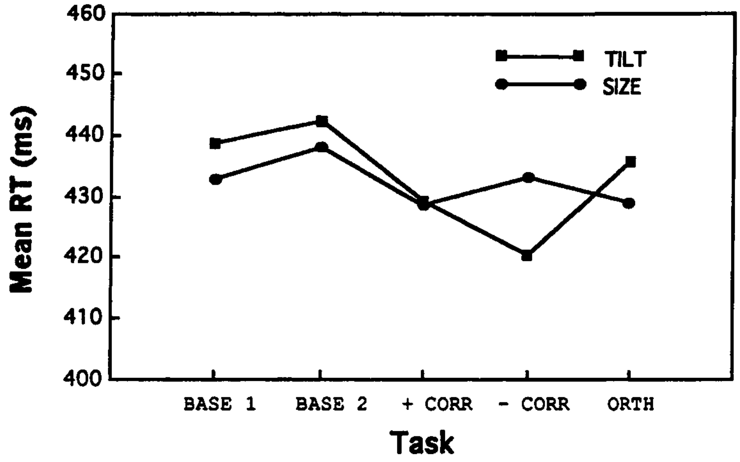


Figure 6. Mean reaction times for tilt and size dimensions as a function of task in Experiment 6.

analytic processing. Such inherent dimensional characteristics have been thought to outweigh other factors and therefore ensure some acceptable level of reliability in defining the appropriate status of a given pair of dimensions, either at one pole of a dichotomy or somewhere along a continuum from integral to separable. In the real world, it is clear that the particular combination of dimensions is just one of many aspects of stimuli and processing that must be taken into account and that the same or similar pairings of dimensions need not produce the same or similar perceptual results in every situation. As Garner (1970) argued, we cannot know without experimenting whether the dimensions specified in the physical world (e.g., by the experimenter) constitute substantive psychological dimensions; therefore, we can define many stimulus configurations as instantiations of particular dimensions, such as "size" or "tilt," but this does not mean that these dimensions are perceived as such. Thus, rather than persist in attempts to identify dimensions as more or less separable, our scope should broaden to include more of the factors or conditions that lead perceivers to exhibit separable processing in one case and integral processing in another. This approach has been advocated by many others as well (e.g., Foard & Kemler Nelson, 1984; Kemler, 1983; Lockhead & King, 1977).

In our experiments, as well as previous studies, changes in performance can be attributed to changes in the psychological salience of the dimensional structure specified by the experimenter. Such changes are probably unconscious on the part of the perceiver (and this is consistent with several comments from our subjects), and when such changes make the dimensional structure less salient, they may hurt rather than "optimize" processing.

As mentioned above, Pomerantz and colleagues (Pomerantz et al., 1989; Pomerantz et al., 1977) have offered a view, in terms of emergent features, that transcends those theories of multidimensional processing that propose a dichotomy or continuum. For Pomerantz and Garner's (1973) stimuli, the emergent feature was configurality. Pairs of parentheses that curved in opposite directions ["( )" or ")("] or in the same direction ["((" or "))"] were processed as a unit and thus exhibited Garner interference when subjects tried to attend to only one element of the pair. Apparently, the Gestalt properties of prègnanz and proximity exerted more influence than did the dimensional structure; although subjects certainly were able to distinguish the orientations of the left and right members of each pair, these elements were neither psychologically useful nor easily attended selectively. We propose that a similar process is responsible for our results as well as those of many previously cited studies with "integral," "separable," and "separate" dimensions.

In Experiments 1–4 of our study, the tilted lines carried incidental information about the size of the circle by specifying the length of the diameter. Because the lines clearly extended to the circle's perimeter, regardless of the circle's size, our subjects perceived the circle-and-line in a more configural manner than the circle-and-(unattached)line of Experiments 5 and 6. This explanation would anticipate the asymmetry of interaction that we observed in Experiments 1–4, because there is a logical asymmetry with these dimensions as well: Variations in size affect the lines that specify tilt, but variations in tilt do not affect the circles that specify size. This explanation cannot account for the results of Experiment 6, however, because this asymmetry was still present and no interaction occurred.

Another plausible explanation for these results is that the juncture served to fuse the dimensions not only physically but also psychologically. An additional assumption is required, then, to explain the asymmetry. One reasonable hypothesis is that because the circle and line were connected, changes in the circle's size led to the perception of the stimuli as different objects (e.g., a small and a large single-spoked wheel) rather than as discrete combinations of circle size and line orientation. As with Pomerantz and Garner's (1973) stimuli, there is no doubt that subjects are able to distinguish size and tilt; dimensional structure is simply not the most psychologically compelling way to make sense of the stimuli, due, in our case, to the coincidental variations in size and length. A testable prediction that follows from this explanation is that making the dimensions more separate (in Shepp's, 1989, sense) will also facilitate attention to the dimensional, rather than the configural, structure, as was seen in Experiment 5. Either having the line terminate even farther from the circle's perimeter or having the line fall outside the circle altogether should produce a pattern of performance consistent with separability (given, of course, an acceptable level of discriminability on both dimensions). Such a manipulation would also help to clarify whether the juncture per se or the shared boundaries of the line and circle were responsible for the interaction.

The present experiments speak to the important distinction, mentioned previously, between experimenter-defined and subject-defined stimulus parameters. In all our experiments, size and tilt were separable according to Shepp's criteria; yet, they never behaved in a truly separable manner until they were altered as in our Experiments 5 and 6. Future studies might seek to predict the level of interaction of visual dimensions depending on whether they (1) share no physical space (such as Hyman & Well's [1968] chroma and value on separate color chips), (2) share some physical space but do not have the same boundaries (i.e., a circle with lines that extend beyond the circle's boundaries, or lines that do not touch the boundaries, as in our Experiments 5 and 6), or (3) share some or all of the same physical space, including their boundaries (such as our circle-and-diameter stimuli).

CONCLUSIONS

Differences in the degree of separability both within and between dimensions can be seen as at least partially a matter of the context in which the dimensions are viewed, rather than as stable characteristics of the pair of dimensions in question. Task instructions can emphasize dimensional structure, similarity, or some configural property. Normal development brings an increase in the ability to attend selectively. Spatial separateness can render dimensions more salient and thus more available for analytic processing. Further empirical support for these preliminary assertions will facilitate development of theoretical statements about multidimensional processing that transcend specific dimensional combinations.

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NOTES

1. Although there is evidence that certain pairings of attributes from different dimensions are processed more effectively than others, the terms *positively* and *negatively* correlated are used only to distinguish the two tasks and are not meant to imply any positive or negative association psychologically.

2. The Huynh–Feldt correction may be needed to correct for lack of sphericity in repeated measures designs when the numerator's degrees of freedom exceed 1. Hereafter, all corrected values of p are given in parentheses.

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