Toward a theory of frontal-size judgments

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A quantitative description of frontal-size judgments is presented in three models. The models are similar in that each is based upon the power function between theoretical and judgment ratios. Within broad limits, the exponent of the function indicates the specific experimental conditions. The Null model describes judgments when stimulus cues are totally reduced, and the visual angles of targets are matched. The Ratio model describes judgments of different target sizes that are all presented at a constant distance. The Distance model describes judgments of targets located at different distances. The common structures of these three models have implications for a theory of frontal-size judgments.

The rationale of this paper is to lay the groundwork for a theory of frontal-size judgments. Specifically, the purpose of this paper is threefold: (1) To define three descriptive size models: the Null, Ratio, and Distance; and to present some evidence in their support. (2) To point out some of the commonalities and differences among the three models. (3) To discuss several implications of these models for a theory of size judgments.

THE NULL MODEL

Null Matches

If a comparison target (T_c) is adjusted to match the size of a standard (T_s) under conditions of total cue reduction, the result is usually a match of their respective visual angles subtended at the eye. Hence, theoretical and judged size relations can be expressed in terms of visual angles as:

$$\begin{array}{ll} \text{Theoretical Size} & \text{Judged Size} \\ T_c = T_s & t_c = f(T_s) \\ \text{or } T_c/T_s = 1.0 & \text{or } t_c/t_s = f(T_c/T_s) \end{array} \quad (1a) \quad (1b)$$

The lower case letters refer to judgments and indicate that computations of visual angles were made after the adjustment of the comparison.

Many experiments conducted for diverse reasons have confirmed the hypothesis that null matches ($t_c = T_s$) are dominant under these conditions, and yet, surprisingly few studies have involved a wide range of standard sizes. One such study was reported by Over (1960) who used a standard target that subtended visual angles ranging from .38 to .95 deg under reduced-cue conditions. This was accomplished by employing several metric sizes placed at several metric distances. Over instructed his observers in two ways: to produce Objective (metric match) size judgments or to produce Projective (visual-angle match) judgments. I have transformed the mean judgments from both instructions into visual angles in order to determine the relationship between theoretical and judged sizes as expressed in Equation 1b. The outcome of these computations is depicted in Fig. 1. The mean comparison size (t_c) is a linear function of the standard size (T_s) for both Objective and Projective instructions. These are null matches, and their accuracy can be assessed by noting the correspondence between the data points and the solid 45-deg line representing a perfect match of visual angles. The maximum deviation from a null match is about 7% for a standard subtending a visual angle of 43 min of arc. These results are simply described by Equation 2.

$$\begin{array}{l} t_c = t_s \\ \text{or } t_c/t_s = T_c/T_s = 1.0 \end{array} \quad (2)$$

For the sake of consistency, t_s is assumed to be equal to T_s .

The validity of Equation 2 has been established in a string of tests involving only one or two standard sizes (Baird, 1963, 1964; Hastorf & Way, 1952; Heinemann, Tulving, & Nachmias, 1959; Lichten & Lurie, 1950; Rock & Ebenholtz, 1959; Rock & McDermott, 1964). I have transformed means and standard deviations from these experiments, and have compared the outcomes with predictions from Equation 2. The judgments approach a null match for all standard sizes, and thereby extend

Fig. 1. Mean size production of a comparison target (t_c) as a function of the size of a standard (T_s). Data are given for Objective and Projective instructions under reduced-cue conditions. The solid 45-deg line represents a match of visual angles.

the validity of Equation 2 to targets of about 3 deg.

Frame Effects

One set of stimulus conditions consistently leads to deviations from a null match. These conditions are present whenever frames of different size are placed around the standard and comparison targets. Consider, first, an experiment by Künnapas (1955). Here, the standard target was a 50 mm line located within a square frame (7 cm on a side). The comparison was a line that was varied in length and was surrounded on successive occasions by different frame sizes (sides = 9, 12, 16, and 21 cm). Null-match judgments were requested for the standard and comparison lines with each comparison frame. The method of constant stimuli was used to obtain this point of subjective equality. A systematic deviation from a null match was found in that a larger comparison line was chosen to match the standard under all conditions, and the size difference increased monotonically with the comparison size. The relation between the two variables was not linear, but it can be shown that size judgments were either a logarithmic or power function of frame size. It is useful to develop a mathematical description of these results. The power function was chosen for this purpose because of its generality to other size results to be reviewed later in this paper. The power function for the Null model is given by Equation 3.

$$t_c/t_s = k (\phi_c/\phi_s)^f \quad (3)$$

Here, t_c and t_s represent the angles subtended by the lines; and ϕ_c , ϕ_s are the visual angles subtended by one side of the comparison and standard frames. After logarithmic transformations of the Künnapas data, the method of least squares was used to determine the values of the parameters of f and k . The exponent (f) is .10, and the constant (k) is 1.0. These findings also can be presented in graph form. For this purpose, the logarithmic form of Equation 4 is commonly applied.

$$\log(t_c/t_s) = f \log(\phi_c/\phi_s) + \log k \quad (4)$$

In Fig. 2 the mean data are plotted according to Equation 4 (logarithmic coordinates). In this graph, the horizontal line through the origin represents a null match of visual angles and the 45-deg line represents the case in which the ratio between the sizes

Fig. 2. Means and standard deviations of ratio productions of targets (t_c/t_s) as a function of ratio frame-sizes (ϕ_c/ϕ_s). The coordinates are logarithmic to accord with Equation 4. The solid 45-deg line represents a ratio match. The horizontal solid line represents a null match of visual angles. Dashed lines are theoretical predictions. For more details, see the text.

of the comparison and standard targets is matched to the ratio between the sizes of the comparison and standard frames. The trend of the Kunnappas results is slightly positive and away from a null match.

The open circles in Fig. 2 are from a study by Rock & Ebenholtz (1959, Table 3), whose null-match data were already mentioned. But the results in Fig. 2, plotted according to Equation 4, are far from null matches. These judgments were performed under reduced cues when different frame sizes surrounded the targets. Actually, a straight-line fit to the means is not very satisfactory, but by least squares solution, the slope of a linear function is .55, assuming a null match for equal frame sizes. The instructions given by Rock and Ebenholtz did not clearly state that a null match was required, and this ambiguity could account for the position of the data points at values intermediate between a null and ratio match. This hypothesis suggests that alternative theoretical stimulus ratios are available with frames, and that an observer would produce different size judgments depending upon the exact ratio he was attempting to produce. For instance, an observer could estimate the ratio of the standard target to the standard frame and then produce this ratio in his adjustment of the comparison target in respect to the comparison frame. This would yield ratios between the two targets that were proportional to the ratios between the frames. This situation is depicted by the 45-deg line in Fig. 2.

There appear to be no experimental data explicitly secured by this judgment method, but it is possible to derive theoretical size judgments from some results of Helson & Bevan (1964, Experiment VI). They had observers estimate the ratio between the area occupied by a center square and the area occupied by a surrounding frame. In one condition, the center square (T_s) was fixed at 53% of the total frame area, although the absolute area of the frame was changed in seven steps between 3 and 147 sq. in. The area of the target was overestimated in respect to the frame, and this overestimation increased monotonically with decreasing frame size. The smaller the frame, the greater the overestimation. What we want to extract from these results is a size value that would be predicted when the task is to produce a ratio between one target-frame combination to match the estimate of the target-frame ratio existing for another combination of different absolute size. It can be shown that these theoretical results are

derived from the Helson and Bevan study by applying Equation 5.

$$t_c/t_s = (x/y) (\phi_c/\phi_s) \quad (5)$$

Here, the value x is the constant by which the standard target-frame ratio must be multiplied in order to give the estimate of that ratio. For the present purpose, the standard was assumed to be the smallest target in the series employed by Helson and Bevan. The value y serves a similar function for each of the comparison target-frame ratios. The remaining variables are defined as in Equation 3. The Helson and Bevan² data were transformed according to Equation 5, and are plotted as filled triangles in Fig. 2. The result is quite interesting. A ratio match is approximated, but not attained, since the judgment ratios increase slightly faster than the frame ratios. A least squares fit of a straight line is excellent, and therefore, the power function (Equations 3 and 4) is valid. The slope (f) of the function is 1.05. Examining the results as a whole in Fig. 2, a pattern emerges. A variety of size judgments are possible (theoretically) with almost identical stimulus conditions, but the general form of these results is similar; only the slope changes.

One final comment about Fig. 2. The results all involve frame and target ratios that exceed 1.0. This restriction depends partly upon the form of data analysis. Symmetrical results should occur when the roles of the comparison and standard stimuli are reversed. These theoretical predictions of symmetry are given by the dashed lines in Fig. 2 extending into the quadrant containing ratios less than 1.0.

THE RATIO MODEL

The Null model presumably concerns only theoretical ratios of 1.0, but in practice observers may judge ratios other than 1.0 when frames are located around the targets. The Ratio model explicitly treats the analysis of size judgments for any stimulus ratio. Most frequently, these judgments are secured by verbal estimation methods (Ekman & Junge, 1961; Stevens, 1956; Teghtsoonian, 1965).

Stimulus Attributes

Judgments of ratios other than 1.0 seldom approach the reliability of null matches. The degree of match between the theoretical and judgment ratios depends upon the attribute of the targets. For example, the estimation of line lengths is accurate, whereas judgments of area are generally less than physical area, and depend upon instructions. Despite these complications, size judgments obtained by ratio methods can be described, almost without exception, by a power function (Stevens & Galanter, 1957; Stevens & Guirao, 1963; Teghtsoonian, 1965). A convenient form of this function is given in Equation 6.

$$t_c/t_s = k (T_c/T_s)^a \quad (6)$$

where the units of measure depend upon target dimensionality. For instance, with stimulus area (surface) the target sizes are measured in units of metric area or as subtended solid angles at the eye. For this reason, it is proper to consider T_c/T_s as a theoretical ratio of stimulus sizes that is defined by the experimenter to fit specific requirements of theory. The judgment ratio (t_c/t_s) also is defined according to the specific situation; for example, in magnitude estimation this ratio is the number assigned to the comparison target divided by the number assigned to the standard (either by the E or by the O).

The exponent (a) in Equation 6 reflects the attribute estimated, though it is not possible to specify the exponent with high confidence. As previously mentioned, length judgments are most reliable, and the exponent is near 1.0, but even here, disparate results are reported (Engen & Ross, 1966; Pitz, 1965). The exponents for stimulus area are particularly variable. Initially, Ekman & Junge (1961) reported that the exponent for area was around 1.0, but later investigators found much lower values.

Teghtsoonian's (1965) study is a good example of the difficulties encountered in specifying an exact exponent for area. She used Apparent and Objective instructions in the method of magnitude estimation. The stimulus targets were a series of two-dimensional figures of various shapes. The exponent for Objective instructions was near 1.0 with circles as targets, but the exponent for Apparent instructions dropped to about .80. Values

around .80 also were common for more complex shapes (hexagons) regardless of instructions. However, there was considerable variability of the exponent for different stimulus shapes and among observers. Actually, Teghtsoonian reports exponents ranging from .60 up to around 1.0 for judgments of area, although the modal exponent with Apparent instructions was .80.

Except for length and area, not much work on size has been published with ratio methods. Some meager data exist for volume, and once again there is disagreement about the magnitude of the exponent. Ekman & Junge (1961) found an exponent around 1.0 for volume judgments of solid objects, whereas the exponent was .79 for two-dimensional representations of cubes (see also Ekman, Lindman, & Olsson, 1961). On the other hand, Teghtsoonian's experiments (1965) yielded exponents between .65 and .74 for solid cubes and octahedrons.

In addition to these experiments, magnitude estimation has been used to obtain area judgments of complex targets (Baird, 1965a). Here, the stimuli were matrices containing different arrangements of black and white squares. Area judgments of these complex targets were not fit very well by a power function; though if this function is used, the exponents are less than .50.

Ratio methods are responsible for our appreciation of the importance of stimulus attributes in size judgments. However, it is impossible at this time to state that these methods give *unique or stable* exponents for particular stimulus dimensions. It may be that one exponent has a higher probability of occurrence than others for a given set of conditions, but these probabilities can only be estimated in a rough way on the basis of existing results. There does seem to be a systematic relation between the size of the exponent and the number of dimensions required to specify the physical characteristics of the stimulus. With *Apparent* instructions, the greater the number of stimulus dimensions, the lower the exponent. This was pointed out first by Teghtsoonian (1965). A second conclusion of importance is that instructions cause gross shifts in exponents. Objective instructions are associated with higher values than Apparent instructions, and it is probable that other instructions would produce other judgment patterns.

Ratio Transformations

Unlike the production methods of the Null model, ratio estimation is the most common approach to secure judgments of ratios other than 1.0. Before forming a union between the Null and Ratio models, it is necessary to transform the results of ratio estimation into those of ratio production. Theoretically, the exponent for ratio production is the reciprocal of the exponent for ratio estimation. Hence, in order to obtain theoretical ratio productions, we take the *ath* root of both sides of Equation 6 to obtain Equation 7.

$$t_c/t_s = k (T_c/T_s)^{1/a} \quad (7)$$

Here, (a) is the exponent for ratio estimation, and (k) is 1.0. Now we are in a position to plot a summary of the data relevant to the Ratio model.³ This summary is shown in Fig. 3, which is based upon the logarithmic form of Equation 7. The interpretation of this figure is the same as for Fig. 2, except in Fig. 3 the abscissa is the theoretical ratio between the comparison and standard target-sizes and not between frame sizes. The horizontal line still represents a null match, and the solid 45-deg line is a ratio match. Note also that the actual logarithms are used in Fig. 3; so for example, a match is given by the value *zero* on the coordinates instead of 1.0. In constructing this summary, the quantitative results just reviewed have been considered, together with appropriate variability measures. Figure 3 is intended as a theoretical guide and not as a hard and fast model. The judgment of size can be predicted within some broad limits, and it is these limits that are given there. The range of predicted exponents for Objective length, area, and volume is between .90 and 1.10; the range for Apparent area falls between .60 and .90; Apparent volume is between .50 and .80; and complex targets have predicted slopes less than .50. Length is judged most reliably under all instructions tried thus far. The reciprocals of these exponents are given in Fig. 3.

Fig. 3. Summary of theoretical power functions for ratio productions of different stimulus attributes. Log judgment-ratios (t_c/t_s) are plotted against log theoretical-ratios (T_c/T_s). For more details, see Fig. 2 and the text.

THE DISTANCE MODEL

It is now established that the phenomenon of size-constancy is a special case of size judgment under full cues with distance variable, and that a variety of judgments is possible with the same stimulus display (Baird, 1965b; Carlson & Tassone, 1967; Epstein, 1963). The purpose of the Distance model is to describe all of these size judgments in a common way. Several theorists have developed Distance models with strong reliance upon the power function, and this approach has proven satisfactory for most instances of size judgment under full cues (Akishige, 1961; Gogel, 1964; Ueno, 1962). These general models consist of relations between size judgments (metric units) and metric distance. Unfortunately, metric units hamper the use of this model in situations appropriate for the Ratio and Null models, which are based upon angular measures.

A descriptive equation using visual-angle measures in the Distance model has been developed by Baird & Biersdorf (1967). Their approach was based upon two principal assumptions: (1) With a standard and comparison target at the same or different distances, the task of the observer is to produce a ratio of sizes (measured as visual angles at the eye) that matches a theoretical ratio. (2) The theoretical ratio depends upon stimulus and instruction factors, not all of which can be specified at this time.

The visual-angle ratio between a standard and comparison target can be defined according to Equation 8.

$$\text{Theoretical ratio: } T_c/T_s = S_c D_s / S_s D_c \quad (8a)$$

$$\text{Judgment ratio: } t_c/t_s = s_c d_s / s_s d_c \quad (8b)$$

The metric sizes and distances of the targets in Equation 8 are theoretical values dependent on the assumption of size-constancy.⁴ It is important to realize that this choice of theoretical values is entirely arbitrary! Since it is not possible to state the exact theoretical ratios that are prominent under different stimulus conditions, consistency in definition is what counts most. After a size judgment is produced, the visual-angle ratio (t_c/t_s) can be computed by Equation 8b. The function between judgment and theoretical ratios is then described according to Equation 9.

$$t_c/t_s = k (T_c/T_s)^d \quad (9)$$

This is identical to the power function used for the Ratio model. It turns out that Equation 9 is valid for most results obtained under full-cue conditions with distance variable.

Fig. 4. Means and standard deviations of ratio productions (t_c/t_s) as a function of theoretical ratios (T_c/T_s). The mean plus one standard deviation is given for Perspective and Objective instructions. The mean minus one standard deviation is given for Apparent and Projective instructions. The targets were presented at various distances and were judged by separate groups of observers under the four instructions indicated. The coordinates are logarithmic. For more details, see the text.

Instructions

The exponent (d) is an indicant of the instructions given to the observer. Four types of instructions have been explicitly defined though they are not used with equal frequency: Objective (metric match), Perspective (visual angle inversely proportional to distance), Apparent (phenomenal, look), and Projective (visual-angle match) (Carlson, 1962; Epstein, 1963). These four types should be considered as a conservative sample of the instructions that have been or could be given in procedures relevant to the Distance model. The interesting aspect of the instruction variable is that it is linked with changes in the magnitude of size judgments.

When the standard and comparison are separated in distance, the theoretical ratios change according to Equation 8a and so do the judgment ratios. The form taken by this change depends upon instructions. Figure 4 depicts means and standard deviations from an experiment by Epstein (1963) who used Objective, Perspective, Apparent, and Projective instructions. The results are for a standard of 7.6 cm, which was placed at distances ranging from 10 to 120 ft. The comparison target was always at 5 ft and that is why all the data points in Fig. 4 are larger than 1.0. Otherwise, the interpretation of Fig. 4 is similar to that of Fig. 3. Straight lines offer tolerable fits to the means for each instruction in Fig. 4. After logarithmic transformations, the original Epstein data were fit by least squares solutions. The slope (exponent) and to a lesser extent the y-intercept depended upon instructions. The empirically determined exponents were: Objective, $d = 1.13$; Perspective, $d = 1.21$; Apparent, $d = .97$; Projective, $d = .68$. The dashed lines in Fig. 4 represent theoretical extensions of the obtained means to include situations in which the comparison is farther than the standard. This relative ordering of instruction effects is consistent when one includes similar analyses of other experiments (e.g., Carlson & Tassone, 1967; Gilinsky, 1955). What should be emphasized is that the results in Fig. 4 are not exceptions. They are backed by substantial data from other investigations (except for Perspective instructions). It is not possible to quote a unique exponent for different instructions, although it is reasonable to make quantitative predictions within some limits. Figure 4 can be used as a guide for these predictions. In addition, the ranges of

slopes for each instruction can be based upon the quantitative data reported in the aforementioned studies. The expected range of exponents for Objective instructions is between 1.0 and 1.20; for Apparent, the range is .90 to 1.10; and for Projective, the range is .30 to .80. The range for Perspective instructions is 1.0 to 1.21, but these values are based only upon Epstein's results.

OVERVIEW

The psychophysical functions for frontal-size judgments have now been summarized. Despite differences in methods, stimulus cues, and target position, all results are accommodated by a coherent model. The similarity of the Null, Ratio, and Distance models is reflected in their structural characteristics. (1) Each of the three contains two variables: theoretical and judgment ratios. (2) Usually, the sizes of targets comprising the ratios are defined in angular units. (3) The unitless nature of the ratios allows all frontal-size judgments to be plotted in the same coordinate system, while the particular units of measure depend upon the experimental procedures. (4) No matter what properties of the stimulus situation are represented by ratios, the power function offers a good empirical description of the results. The most invariant part of this function is the null match which occurs within a remarkably broad range of instructions, psychophysical methods, and stimulus cues. This special ratio (1.0) is a pivot point through which all functions should pass; whereas, judgments of other ratios deviate from matches in a systematic way.

The two major variables that effect the magnitude of exponents are stimulus attributes and instructions. Neither of these variables has been adequately quantified independent of responses. However, the overall evidence points toward a particularly simple relationship among these variables and the stimulus environment. The environment seems to offer alternative stimulus-ratios that depend upon the available visual cues. Instructions direct the observer to judge one or the other of these alternative ratios. After a ratio has been singled out, the stimulus attribute further limits the magnitude of the judgment. Therefore, the visual cues, instructions, and attributes can be treated as the primary independent factors in a theory of frontal size. This possibility now will be explored somewhat further in order to highlight some common features of the frontal-size models.

Null and Ratio Models

The functions in Fig. 2 for the Null model were based upon the key assumption that Os can judge different theoretical ratios when frames surround the targets than when frames do not. The same stimulus can be judged differently depending upon the O's choice of theoretical ratios. In some instances the frames have no influence upon size judgments and null matches occur; on other occasions, the theoretical ratios are defined by the relative sizes of the targets to their frames, and the exponents shift. This brings us to the crucial point: whatever the theoretical ratios in the Null model, once they are identified, size results should adhere to predictions of the Ratio model. It necessarily follows that many findings within one model await discovery in the other. For instance, the magnitude of frame effects should depend upon target attributes.

Null and Distance Models

The functions within the Null and Distance models coincide to a considerable extent, as is seen by comparing Figs. 2 and 4. This coincidence generates many hypotheses about the judgment process, but only one is expanded here. If the results and procedures of the Null and Ratio model are compared, it can be concluded that the diverse exponents in the Null model were due to the judgment of different theoretical ratios. However, neither of these models states what operations lead to changes in theoretical ratios. On the other hand, the Distance model shows that instructions are associated with shifts in exponents. But there is no evidence within the Distance model to suggest what it is that instructions alter. Obviously, then, the information gained from the Ratio, Null, and Distance models is complementary. Given a stimulus environment with alternative theoretical ratios, the instructions prescribe the particular ratio (or set of ratios) that the

O is supposed to judge. This implies something concrete and testable about the judgment process. For instance, the overconstancy effect (slope > 1.0) found so frequently with Objective instructions (Fig. 4) may be the natural result of the judgment process implied by the Null model. That is, when a target is surrounded by a frame (or perhaps an adjacent stimulus) the ratio judgment of the target to its frame depends upon the absolute sizes of both (Helson & Bevan, 1964; Fig. 2). Small targets are overestimated relative to their frames, as contrasted with the estimation of the same ratio formed by larger targets and frames. Now in the Distance model, a near target and frame (or adjacent stimulus) subtends a larger visual angle at the eye than do the farther targets and frames. Therefore, in order to match the near target-frame ratio to the far target-frame ratio, the near target will have to be enlarged, according to the predictions of the Null model. This is overconstancy. The effect is shown unequivocally in the slopes greater than 1.0 in Figs. 2 and 4. It is important to note that this prediction could not be made if the size models were based upon metric measures. In particular, the connection between models depends upon the fact that a target of constant metric size subtends a diminishing visual angle as its distance increases.

Ratio and Distance Models

The common elements of the Ratio and Distance models suggest many interesting leads for future research (see Figs. 3 and 4). For example, an explanation of overconstancy can be based upon the Ratio model. Since most of the exponents within the Ratio model are greater than 1.0, overconstancy in the Distance model should be commonplace, and should depend upon the attribute being judged. Linear extent should yield the smallest amount of overconstancy; area, a larger amount; and volume and complex figures, the most. But attribute effects are not the whole story behind the range of slopes in Fig. 4. The overlap between slopes due to attributes and slopes due to instructions is too slight. For instance, Projective instructions have no corresponding functions in the Ratio model. In other words, instruction and attribute effects are largely independent.

Once again it should be noted that predictions of attribute effects in the Distance model are based upon the premise that theoretical visual-angle ratios change with target distance. There appears to be no way an analysis using metric units could generate these predictions unless distance were added to the equations as a separate variable. The latter approach is reflected in the size-distance-invariance hypothesis (Epstein, Park, & Casey, 1961). The failures of this hypothesis, *except for limited conditions*, have been clearly exposed in a series of empirical studies by Baird (1963), Epstein (1963), Gogel (1964), and others.

The Null, Ratio, and Distance models point the way toward a theory of frontal-size judgments. Perhaps the most important aspect of these models lies in the similarity of results coupled with dissimilar experimental procedures. The same judgments can be predicted from several premises about the judgment process. The models make redundant predictions. One of the real advantages of this situation is that results in one model can be used to predict undiscovered functions in another.

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NOTES

1. This work was supported (in part) by a Public Health Service postdoctoral fellowship (Number 1-F2-20, 952-01) from the National Institute of Mental Health, Public Health Service. During the tenure of the fellowship I was working in the Laboratory of Psychology, University of Stockholm. I am indebted to Professor Gösta Ekman for sponsoring my research there. Current address: Psychology Department, Dartmouth College, Hanover, New Hampshire 03755.
2. The argument works for either area or linear extent. I am indebted to these authors for sending me the raw data.
3. Here the Ratio model refers to size productions as a function of theoretical ratios. Note that the theoretical ratios (T_c/T_s) in Equation 7 are comparable to the judgment ratios (t_c/t_s) in Equation 6; and vice versa.
4. More complex formulas are needed when targets are not in a frontal plane. Equation 8 could not be used in the original study by Baird & Biersdorf (1967).

(Accepted for publication March 4, 1968.)