

## Perceiving the Size of Trees: Form as Information About Scale

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Physical constraints on growth produce continuous variations in the shape of biological objects that correspond to their sizes. The author investigated whether 2 such properties of tree form could be visually discriminated and used to evaluate the height of trees. Observers judged simulated tree silhouettes of constant image size. Trees were placed appropriately within a ground texture gradient, as were 6 cylinders. Observers judged trees, then cylinders. Tree form was shown to confer a metric on ground texture gradients. Different observers judged cylinders without seeing trees. The horizon ratio was shown to be ineffective as an alternative source of scale. The largest trees were systematically underestimated. Comparison was made to judgments of real trees viewed binocularly, monocularly through a tube, or in pictures. Underestimation of larger trees with restricted viewing was comparable to that obtained using simulated trees.

[O]rganisms cannot violate the laws of physics and chemistry. . . knowing how these laws operate and confine the organismic expression of size, form, and structure is essential to understanding biology . . .

Nowhere else in biology than in plants do we find such convincing evidence that physical laws and processes link form with function and thus have confined the scope of organic expression within boundaries that have never been breached. K. J. Niklas (1992, pp. ix, 6.)

The problem of size perception arises because the size of the image projected from an object varies with the distance of the object from the observer. Image size alone provides no information about object size. The traditional solutions to this problem are size-distance invariance theory and familiar size.

In size-distance invariance theory, the inverse relation between image size and object distance is used to derive perceived object size, assuming that information about distance is available (Boring, 1940; Epstein, 1977; Gogel, 1977;

Hochberg, 1978; Holway & Boring, 1941; Kilpatrick & Ittelson, 1953; Lian, 1981; Schiff, 1980). This confounds the problems of size and distance perception. Because distance perception is itself a difficult problem, an independent approach to size perception would be advantageous. Familiar size does not presume information about distance. For this reason, familiar size is usually included among hypothetical sources of information about distance (Epstein, 1961; Gibson, 1950; Gogel, 1977; Hartmen & Harker, 1957; Higashiyama, 1984; Hochberg, 1978; Predebon, 1990; Schiff, 1980).

The familiar size solution is simply that the observer knows the size of certain identifiable objects that have highly stable and definite sizes. Familiar size reduces size perception to form perception because object recognition is achieved by identifying characteristic forms. Familiar size is usually considered with respect to constructed objects such as playing cards, matchbooks, and watches because the relevant forms are distinct and the sizes are well restricted. Regularity and predictability are produced by constraints impinging on the formation of the objects in question. The nature of human activity and the associated scale constrains the sizes and shapes of constructed objects (Drillis, 1963). Human factors and ergonomics comprise efforts to describe such constraints on the forms of tools, furniture, and buildings. Because the sizes of such objects derive from human scale, they are determined indirectly by constraints on the sizes of people, a type of biological object. The sizes and forms of biological objects, in turn, are constrained by physical and biological laws (Niklas, 1992). The study of such laws comprises functional morphology and allometry (Calder, 1984; Hildebrand, Bramble, Liem, & Wake, 1985; McMahon, 1984; McMahon & Bonner, 1983; Niklas, 1992; Norberg, 1988; Peters, 1983; Schmidt-Nielsen, 1984; Thompson, 1961; Wainwright, Biggs, Currey, & Gosline, 1976).

The application of familiar size to biological objects would seem to be difficult because the sizes for a given type of object are less restricted and the relevant forms are more complex and subject to continuous variations. However, allometry reveals that those variations are scale specific. In his classic work on morphology, D'Arcy Thompson (1961) de-

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scribed organic form as a "diagram of forces" and, following observations of Galileo, noted that organic forms alter in the face of scale changes to preserve the integrity of structure and function.<sup>1</sup> The forms must change because an object's various linear and geometric dimensions scale differently to relevant forces. For instance, as discussed by Galileo, the strength of a bone required to support its weight is proportional to the square of its diameter, whereas the weight to be supported is proportional to the cube of its length. As a bone increases in size, its diameter must increase faster than its length in order to support the weight. Bigger bones must be relatively thicker. Such changes in form are especially prominent in biological objects because their materials remain invariant over scale changes wrought by growth.

Can observers use continuous variations in form to perceive variations in size? If so, the generalization would make the familiar size solution very powerful. However, generalization depends, in part, on discriminative abilities in form perception. Pittenger and Todd (1983) demonstrated that continuous variations in the form of the growing human body from infancy to adulthood could be discriminated by observers who used the information to judge age levels. Also, the perception of age by means of the continuously transforming shape of the head over growth has been studied extensively in work that partly inspired the current approach to size perception (Mark, Todd, & Shaw, 1981; Pittenger & Shaw, 1975a, 1975b; Pittenger, Shaw, & Mark, 1979; Shaw, Mark, Jenkins, & Mingolla, 1982; Shaw, McIntyre, & Mace, 1974; Shaw & Pittenger, 1977; Todd & Mark, 1981; Todd, Mark, Shaw, & Pittenger, 1980).

What of variations in the forms of plants? Observers can certainly distinguish a stalk of grass from a tree. The forms are fairly distinct. Is the same true of small versus large trees? In this instance, the size can vary continuously from a foot to a hundred feet. Do specific continuous variations in tree form accompany such variations in size? If so, can observers distinguish such variations in form and use this information to evaluate size?

Studying the perception of tree sizes provides a good test case for a reduction of size perception to form perception by virtue of physical constraints on form. First, trees are extremely common in the visual environment, and they include the range of sizes directly relevant to human activity. Their presence could be used to determine the size of neighboring objects, including human artifacts (e.g. buildings) and terrain features (e.g. rock outcrops). Second, their frequency of appearance in the surround means that observers will be familiar with them. Third, tree morphology has been studied extensively. Some of the scaling laws that determine changes in form accompanying changes in size with growth have been described (Borchert & Honda, 1984; Borchert & Slade, 1981; Fisher & Honda, 1977, 1979a, 1979b; Honda & Fisher, 1978; Honda, Tomlinson, & Fisher, 1981; McMahon & Bonner, 1983; McMahon & Kronauer, 1976; Niklas, 1992; Norberg, 1988; Turrell, 1961; Wilson & Archer, 1979; Zimmermann, 1978a, 1978b). Fourth, the same scaling laws apply to most other forms of terrestrial vegetation, and some apply as well to aspects of the form and structure of vertebrates (McMahon, 1984; McMahon & Bonner, 1983; Peters, 1983).

Fifth, the relevant forms are complex and the variations in form are sufficiently subtle to provide a good test of the ability of the visual system to detect subtle variation in complex forms and use it as information about size.

Two scaling laws are known to determine characteristic properties of tree form that vary with tree height. First, successful mechanical support is achieved in trees by preserving elastic similarity (McMahon, 1975; McMahon & Kronauer, 1976; Niklas, 1992; Norberg, 1988). The diameter ( $D$ ) of a branch or tree trunk scales with the remaining length along the branch or height ( $H$ ) of the trunk to its tip as follows:  $D = a(H)^{1.5}$ . This is consistent with an empirically derived relation, which also is dependent on maximum heights for given climate zones (Kira, 1978). (See Appendix A). The relation between diameter and height in this latter case is hyperbolic:

$$D = \frac{MH}{a(M - H)}, \quad (1)$$

where  $M$  is the maximum height for trees in a given climate zone. Both relations predict that the ratio of the diameter of the trunk to the height of a tree is specific to the actual height of the tree. (This ratio also applies to any point along a branch using the diameter at that point and the remaining length to the tip.) Equation 1 determines a relation between actual tree height and  $H/D$  of the form  $H = M - k[H/D]$ . Because the  $H/D$  ratio is well preserved in tree images (see Appendix B), the relation determines optical information for tree height.

Second, the number of terminal branches in a tree scales with the size of the tree (Borchert & Honda, 1984; Turrell, 1961). To collect light a tree covers approximately the surface of its branching volume with leaves of constant size. Branches are required in constant proportion to the leaves. An exponential branching process is constrained by the hydrodynamics of the nutrient distribution, producing conformity to a surface law (Borchert & Honda, 1984; Honda, Tomlinson, & Fisher, 1981; Zimmermann, 1978a, 1978b). This understanding has been confirmed (Kira, 1978; Turrell, 1961) and allows one to predict  $N = b(H)^2$ , where  $N$  is the number of branches and  $H$  is tree height. Thus, the number of branches, a property well preserved in images, also provides information about tree height, as follows:  $H = c(N)^{.5}$ , where  $c = 1/(b^{.5})$ .

### Experiment 1: Judging Isolated Silhouettes and Real Trees

Can observers use forms generated by such scaling relations to judge tree size? To investigate this question, we used the two scaling relations to generate tree silhouettes. To isolate tree form as information about size, image height was held constant over variations in actual modeled tree height.

<sup>1</sup> Similar considerations are found in the study of scale models in engineering where object form and materials must be distorted or altered in small-scale models to preserve structural integrity and function for purposes of testing (Baker, Westine, & Dodge, 1973; Emori & Schuring, 1977; Szücs, 1980).

Silhouettes were presented without information about distance. According to size-distance invariance theory, such displays would contain no information whatsoever about tree heights.

The intention was to ask observers to judge the height (in feet) of simulated trees. To evaluate their performance, we required a standard for comparison. How well might observers judge the heights of real trees under natural (but otherwise comparable) viewing conditions? To address this question, we asked observers to judge the height of real trees on the Indiana University campus from distances that preserved a constant tree image height. Following this, observers judged tree silhouettes on white paper, each appearing without image background structure.

### Method

**Participants.** Twenty-four graduate or undergraduate students at Indiana University participated in the study. Twelve were men, and 12 were women. All had normal or corrected-to-normal vision. Participants were paid at \$4.25 an hour.

**Display generation.** We obtained from Rolf Borchert the program used to generate the simulations of tree-branching processes that were reported in Borchert and Honda (1984). This program was originally written by Honda (1971) to produce images of stick figure trees in architectures determined by varying branching angles and lengths. The program was modified by Borchert and Honda (1984) to include simulation of the hydrodynamic processes (Zimmermann, 1978a, 1978b), which constrain branch numbers to conform to a square law of increase. The program was further modified by adding the Kira relation to determine branch and trunk thicknesses. A maximum tree height of 40 m was used. This is appropriate for temperate zone trees according to the data reported in Kira (1978). The coefficient in the Kira relation was set to a value appropriate for trees growing in isolation. In coupling the scaling for thickness and for branching, we effectively set the coefficient of the branch scaling on the basis of an assumed leaf terminal rosette size of .5 m<sup>2</sup>.

Unfortunately, we did not have descriptions of temperate zone architectures that described trees in terms of branching characteristics. The extant literature addresses tropical trees because architectures in other climate zones correspond to a subset of those found in the tropics (Borchert & Tomlinson, 1984; Hallé, Oldeman, & Tomlinson, 1978; Honda, 1971; Tomlinson, 1983). Without attempting to model specific species of temperate zone trees, we manipulated the architectural parameters to produce seven different architectures that were similar to familiar types. These are shown in Figure 1. We selected these architectures on the basis of their appearance. We also determined the number of orders (or years) of growth generated for each architecture on the basis of appearance. If allowed to iterate too far, the branching algorithm in some architectures eventually produced trees of bizarre appearance. (For instance, Architecture D, which is similar to a small fruit tree, began to look quite strange at higher orders.<sup>2</sup>) Successive heights used in Architecture C are shown in Figure 2.

In the 7 architectures, images of 56 trees of varying height were generated. The simulation painted the thickness on stick figure trees projected on a plane that contained the trunk and was perpendicular to the line of sight. To avoid foreshortening of these flat cardboard diameters we used parallel projection, drawing the trees as if seen from a great distance and then magnifying to achieve significant and invariant image heights. Black silhouettes of 9-cm-high trees were

printed on a white and unstructured surround. A laser printer was used to print the images on sheets of paper that measured 19 square cm.

**Procedure.** Observers first estimated the height (in feet) of 16 actual trees observed on the Indiana University campus at distances that preserved constant image heights of 32° of visual angle. In pilot studies (Bingham & Gutjahr, 1990a, 1990b), we had observed participants estimating their eye heights at the base of a tree and then using this as a yardstick moved successively up the tree by eye. In subsequent studies we mentioned to observers that tree height might be estimated in this manner, but that we did not wish them to do so. Rather, they were instructed to keep their eyes to the ground until they were placed in the desired location for judging a given tree. The tree would then be pointed out to them, and they were asked to glance at the tree only long enough to take in its form and then to produce an off-the-cuff estimate within about 2–3 s. Producing estimates in such a brief interval did not allow observers to use the more explicit measurement technique. Before making judgments, observers were shown two lighting poles and were told that their heights were 26 ft and 64 ft (7.91 m and 19.47 m, respectively). The lighting poles were never in view together with any of the trees judged.

We determined actual heights by sighting the tree top and base and recording the angles of the sight lines to the horizontal, by measuring the horizontal distance from the sighting location to the tree and using the trigonometry described in Appendix B. Actual heights ranged from 10 ft to 90 ft (3.05 m to 27.43 m).

Observers next returned to the laboratory and judged the heights of trees in simulated tree images. Observers were given a packet in which the images of the 56 trees were stapled together in a random order. Two different random orderings were used. Observers were instructed to flip through the images in order, to write estimates of tree height in feet on another sheet of paper; they were told to treat the images as pictures of actual trees, and to judge actual tree heights. After they had completed the entire packet, they were allowed to go back and look at any image they wished and to write adjusted estimates next to their original estimates.

Observers were instructed to judge actual heights of both real and simulated trees; in other words, "objective size" instructions rather than "phenomenal size" or "projective size" instructions were used (Epstein, 1967).

### Results and Discussion

In light of the brief time given to observers, their estimates of the heights of real trees were surprisingly accurate. We regressed judged heights linearly on actual heights separately for each observer. The mean  $r^2$  was .91 ( $SD = 0.06$ ), the mean slope was .97 ( $SD = 0.29$ ), and the mean intercept was  $-.75$  ( $SD = 5.04$ ). One observer produced an exceptionally

<sup>2</sup> From these observations, it is clear that the two scaling laws can only be a part of the full story. For instance, root geometries that are related to above-ground architectures play an important role in determining growth potential (Niklas, 1992). Furthermore, the two laws, which act in parallel in our simulation, ultimately interact. The biomass required for mechanical support of deployed leaves determines a cost to be paid by means of the functioning of those leaves (Ford, Avery, & Ford, 1990; Ford & Ford, 1990). Nevertheless, the two laws, and especially the relation determined by the need for stable self-supporting structures, apply invariantly over variations associated with other constraints on growth in trees.

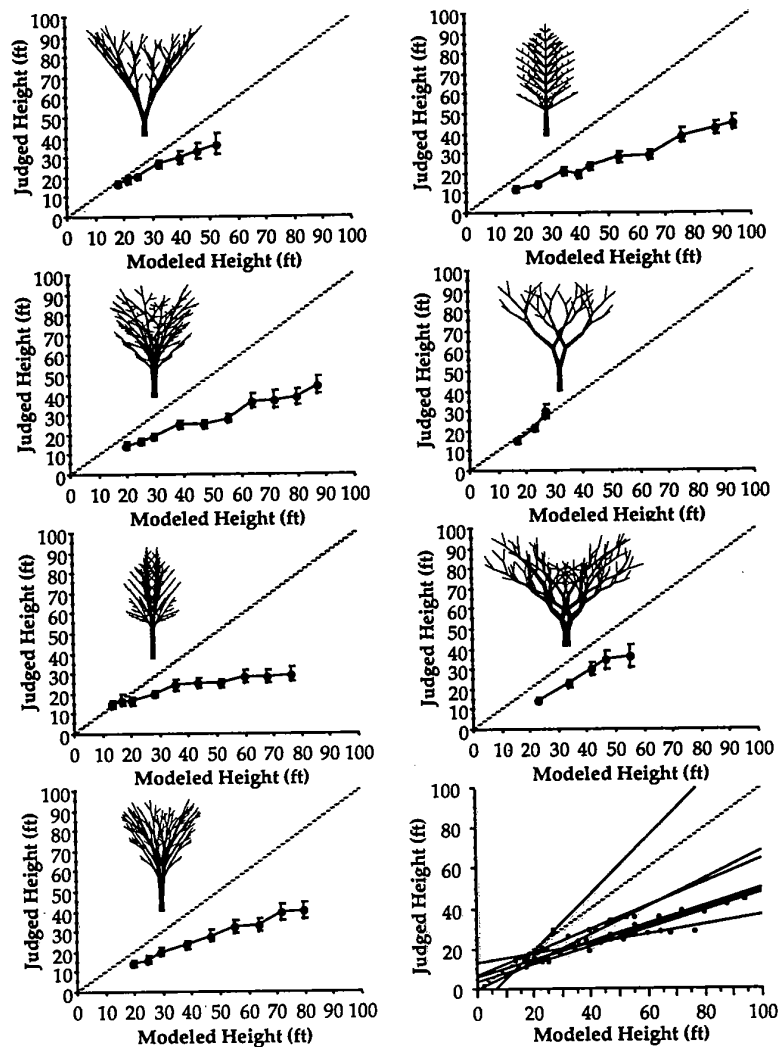


Figure 1. Experiment 1: Mean height estimates (with standard error bars) plotted against modeled heights for each of seven architectures. Images of mid-range trees also are shown for each architecture. Proceeding from left to right and top to bottom (with standard errors in feet of the average deviations of judged height from modeled height for each architecture): (a) Architecture H (1.20 ft), (b) Architecture P (1.20 ft), (c) Architecture C (1.25 ft), (d) Architecture D (1.14 ft), (e) Architecture L (1.32 ft), (f) Architecture M (1.65 ft), (g) Architecture V (1.21 ft), and (h) means for all seven architectures plotted together, each with a least-squares best fit line. The stippled diagonal in each plot is a line of slope 1, intercept 0.

high slope that was more than two *SDs* beyond the mean slope. When his data were excluded, the mean slope was .93 ( $SD = 0.23$ ); the mean intercept and  $r^2$  were essentially unchanged. When a regression was performed on the collected data of 23 observers, the  $r^2$  was .82. Mean judgments are shown in Figure 3a.

Estimated heights of trees in simulated tree images increased with increasing modeled tree height. However, the tendency for increasing underestimation with increasing height was much more pronounced when tree images were used rather than real trees. Random errors both within and

between observers also were significantly greater. The slope of a linear regression of judged height on modeled heights was shallow (.37), with an intercept of 10.2 and an  $r^2$  of .23. When modeled height was regressed separately on judgments for each observer, the mean  $r^2$  was .50 ( $SD = .18$ ). Mean results were plotted by architecture in Figure 1. Observers estimated accurately the heights of smaller trees, but larger trees were underestimated by about 50%. Maximum mean judgments reached only about 50 ft. Results for the L architecture were particularly poor. Observers in a subsequent experiment judged this architecture to

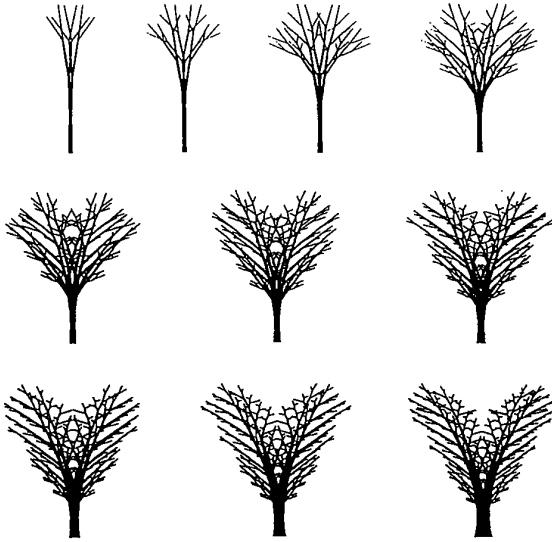


Figure 2. Images used in Experiment 1 of successively taller trees over 10 orders of growth in Architecture C.

be relatively unnatural in appearance as did tree morphologists. We excluded the L architecture from further analysis and investigation.

Next we examined the use of the simulated forms as information about tree height by regressing mean judgments on  $H/D$  and on  $N^5$ , respectively. The relation between modeled heights and  $H/D$  is shown in Figure 4a. The scatter in the relation was a product of architectural variations. Because the length of the branch or trunk was used in the Kira (1978) scaling relation, the coefficient in the relation yielding tree height varied depending on the orientation of the trunk. For a central trunk tree with a vertical trunk, the tree height is the same as trunk length. For angled trunks, tree height is less than trunk length. The slope of the relation between  $H/D$  and modeled heights was larger in central trunk trees and decreased as the main trunks angled out more. Steeper slopes ( $\approx -3$ ) were exhibited by architectures P, C, and V, and shallower slopes ( $\approx -2$ ) were exhibited by architectures H, M, and D. The overall relation was linear, as determined by the Kira model.

In contrast, modeled height was expected to scale to the square of the number of branches. Thus, the relation between modeled height and the square root of the number of branches should have been linear. A linear regression of modeled height on  $N^5$  was significant ( $r^2 = .90$ ). However, as shown in Figure 4b, some residual curvature remained. The second order term in polynomial regressions was significant when modeled heights were regressed on both  $N$  and  $N^5$ , with curvature concave down in the former case and concave up in the latter. The implication was that the exponent in the scaling of branch number on height was slightly less than 2. When  $H/D$  and  $N^5$  were regressed simultaneously on modeled heights, only the latter factor was significant (partial  $F = 55.6$ ,  $\beta = 0.82$ ,  $p < .001$ ). Of course,  $H/D$  and  $N^5$  correlated highly with one another ( $r^2 = .81$ ).

When mean judgments of simulated trees were regressed on  $H/D$ , the  $r^2$  of .93 was greater than for modeled heights as shown in Figure 4c. The intercept was 56 ft. This is maximum tree height in the Kira (1978) model and was almost exactly half that produced by the model. Furthermore, architectural variations in this relation were not reflected in the judgments as shown in the comparison between Figures 4a and 4c. This failure also produced the variation in slopes of height judgments of different architectures shown in Figure 1h. That is, the relative tightness of the relation in Figure 4c and the disparity of the relations in Figure 1h were both reflections of a failure to discriminate architectural variations in the scaling of  $H/D$ .

When mean judgments were regressed on  $N^5$ , the  $r^2$  of .87 was comparable to that for modeled heights. As shown in Figure 4d, however, no residual curvature remained. A polynomial regression also produced a straight line with a nonsignificant second-order term, and a polynomial regression performed with  $N$  was strongly concave downwards with a significant second-order term ( $p < .001$ ). The implication of this was that observers used square law scaling even if the scaling exponent for the simulation was slightly less than 2. When mean judgments were regressed simultaneously on  $H/D$  and  $N^5$ , both were significant, and they accounted for 95% of the variance (for  $H/D$ , partial  $F = 73.8$ ,  $\beta = -0.64$ ,  $p < .001$ , and for  $N^5$ , partial  $F = 22.6$ ,  $\beta = 0.36$ ,  $p < .001$ ). These results implied that observers relied somewhat more on  $H/D$  than on  $N^5$ . We had used simulations in pilot studies that varied only the  $H/D$  ratio, not branch number. An important result in that instance was that some observers had refused to perform the task and others had complained because the information was contradictory. We inferred accordingly that that  $N^5$  remained a relevant source of information despite heavier reliance on  $H/D$ .

We ordered the results of individual observers on the basis of the  $r^2$  values and selected the top half, with  $r^2 \geq .50$ . A multiple regression of mean judgments from this group on  $H/D$  and  $N^5$  accounted for 95% of the variance with  $|\beta| = .50$  in both cases. The maximum height implied in the simple regression of means on  $H/D$  was 70 ft,  $y = -1.65x + 70$ ,  $r^2 = .90$ .

We measured the trunk diameters (above the root swell) of the real trees judged outdoors and computed the corresponding  $H/D$  ratios. The result of a regression of mean judgments on  $H/D$  was as follows:  $y = -1.59x + 98$ ,  $r^2 = .45$ . When the regression was performed using actual heights rather than judged heights, the result was  $y = -1.55x + 99$ ,  $r^2 = .40$ .

The simulation results indicated that the observers' use of the  $H/D$  ratio was not scaled differently for different architectures. As previously mentioned, the relation between  $H/D$  and modeled height was different for different architectures. The slopes were shallower for Architectures M, D, and H, and steeper for the others. The intercepts, indicating maximum heights, also were significantly lower for Architectures M, D, and H. This was appropriate for Architectures D and M, in particular, because these architectures ceased growing upward after a given branching order and thereafter continued to grow only outward.

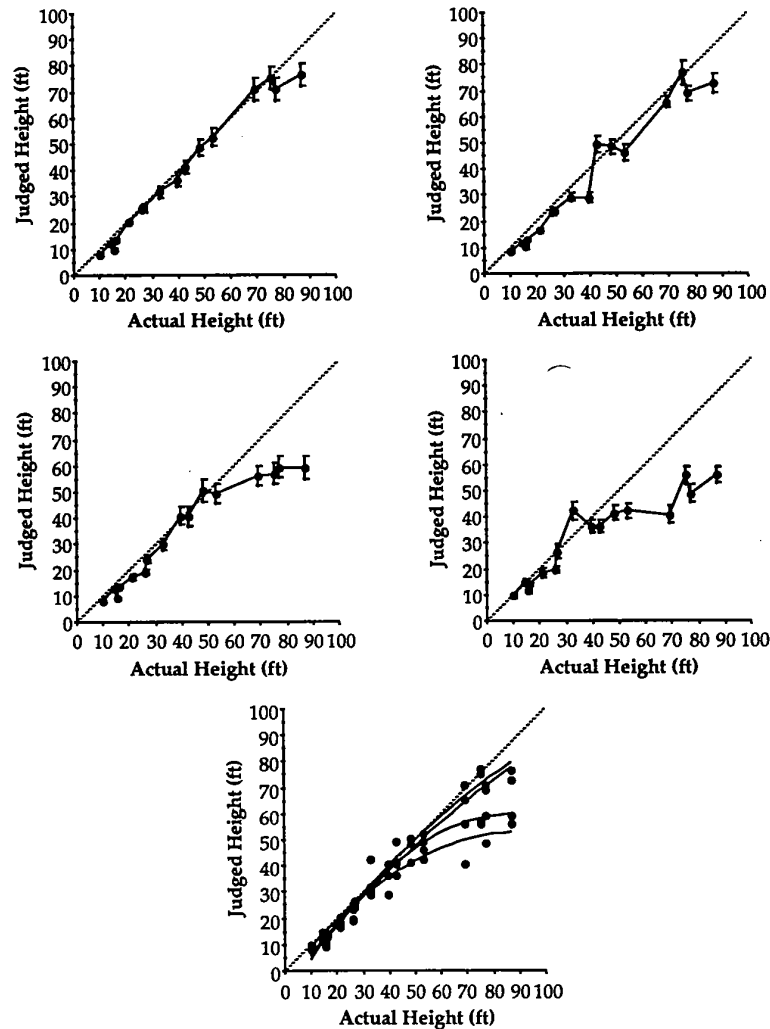


Figure 3. Mean height estimates (with standard error bars) of 16 real trees plotted against actual heights for each of four viewing conditions (proceeding from left to right and top to bottom): (a) trees with leaves (Experiment 1), (b) trees without leaves (Experiment 3), (c) trees viewed through a tube, (d) trees viewed in photographs, and (e) means for all four viewing conditions plotted together, each with a least-squares best fit second-order polynomial curve. See the text for explanation of viewing conditions and description of the curves. The stippled diagonal in each plot is a line of slope 1, intercept 0.

Although Architecture M ceased growing upward, it did continue to grow. In general, architectural variations determined how much of the increase in size with increasing growth order was contributing to increases in height. In a central trunk tree like Architecture P, increases in size entirely corresponded to height increases. In the other architectures, as the main trunks angled outward more, size increases contributed less to increases in height. This was especially evident in Architecture M. This observation raised the question of whether observers might be able to judge size variations other than height in simulated trees.

#### Experiment 2: Judging the Size and Realism of Simulated Trees

Trees (and other plants) grow in size by extending the lengths of their branches. To the extent that the branches are not oriented vertically, increases in size and in height will not be equivalent. We investigated whether observers could estimate the sizes of simulated trees and whether the pattern of size judgments would be different from that of height judgments. Trees with trunks angled away from the vertical

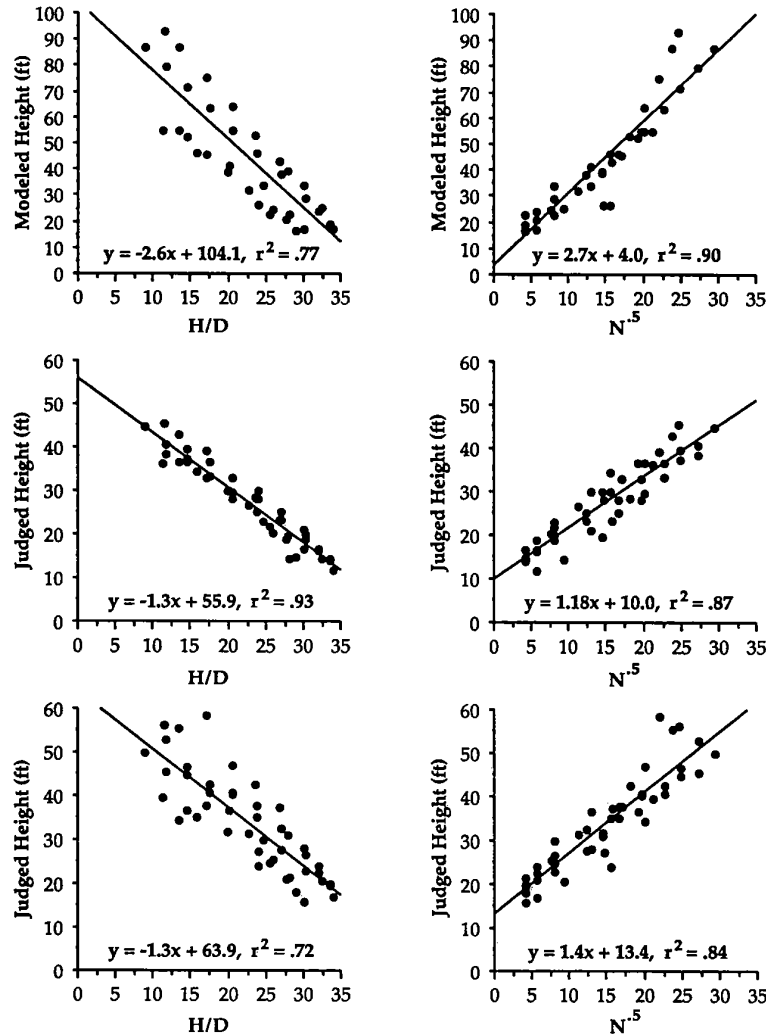


Figure 4. Modeled and mean judged heights for 46 simulated trees plotted against either the  $H/D$  ratio or the square root of the number of branches,  $N^{.5}$ , each together with the results of a simple linear regression. Proceeding from left to right and top to bottom: (a) modeled heights versus  $H/D$ , (b) modeled heights versus  $N^{.5}$ , (c) mean judged heights from Experiment 1 versus  $H/D$ , (d) mean judged heights from Experiment 1 versus  $N^{.5}$ , (e) mean judged heights from Experiment 3 versus  $H/D$ , and (f) mean judged heights from Experiment 3 versus  $N^{.5}$ .

should be judged to be of relatively greater size than height compared with vertical central trunk trees.

### Method

**Participants.** Twenty-six graduate or undergraduate students at Indiana University participated in the study. Half were men and half were women. All had normal or corrected-to-normal vision. Participants were paid \$4.25 an hour.

**Procedure.** The simulated tree images from Experiment 1 were used to elicit estimates of tree size. Observers were asked to judge the size or massiveness of trees on an arbitrary scale of 1 to 100; they were reminded that trees grow outward as well as upward as

they increase in size and that they should take this into account. The procedure used was the same as in Experiment 1.

When observers had completed their estimates of size, they were asked to judge the trees in terms of the realism or naturalism of the tree images. Observers judged realism on a scale of 0–8, where 8 was defined as “an actually existing tree” and 0 as “an impossible tree.”

### Results and Discussion

We first review results of realism judgments and then turn to size estimates. The simulated tree images were judged to be fairly realistic. The overall mean judgment was 4.5. When

a repeated measures analysis of variance (ANOVA) was performed on judgments with tree architecture as a factor, architecture was significant,  $F(6, 144) = 12.8, p < .001$ . In a Tukey honestly significant difference paired comparison test, Architectures L and P were different ( $p < .05$ ) from all other types. As shown in Figure 5, L was rated lower than the other architectures, with an overall mean of 3.2, whereas P (at 5.5) was rated higher.

Judgments also varied over growth orders within each architecture. In most cases, the smallest initial orders of growth were rated significantly below the remaining orders. We examined means for each order of growth computed across architectures. The first-order mean was 2.8. This increased linearly up to the fourth-order mean of 5.5. This value was maintained out to the seventh order, where means dropped again to values of 4.5 to 5 for orders up to 10. As shown in Figure 5, this inverted U-shaped pattern of judgments was obtained for Architectures H, C, and V, whereas means for P, D, and M simply rose to a maximum value maintained thereafter. In general, the simulations were judged to be not entirely convincing for smaller trees and for some very large trees as well. These results undoubtedly reflect the shortcomings in the model of the determinants of tree morphology. (See also footnote 2.) Our simulations were examined by Rolf Borchert and other tree morphologists, who agreed that the L architecture appeared less realistic. In view of the concurrence in the poor evaluations of the L architecture by tree morphologists and our naive observers, we excluded the L architecture from further analysis.

We wished to compare estimates of tree size with those of tree height from Experiment 1. Because size and height judgments were performed on different scales, they were reduced

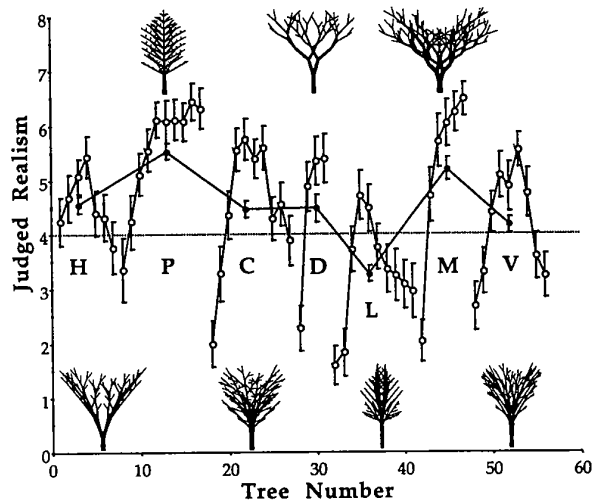


Figure 5. Mean realism judgments (with standard error bars) for 56 trees plotted left to right by increasing growth order within architecture (open circles). The overall mean (with standard error bar) for each architecture also is shown (filled circles). A tree image for the architecture appears either above or below the corresponding judgments. Realism judged on a scale of 0 (an impossible tree) to 8 (an actually existing tree).

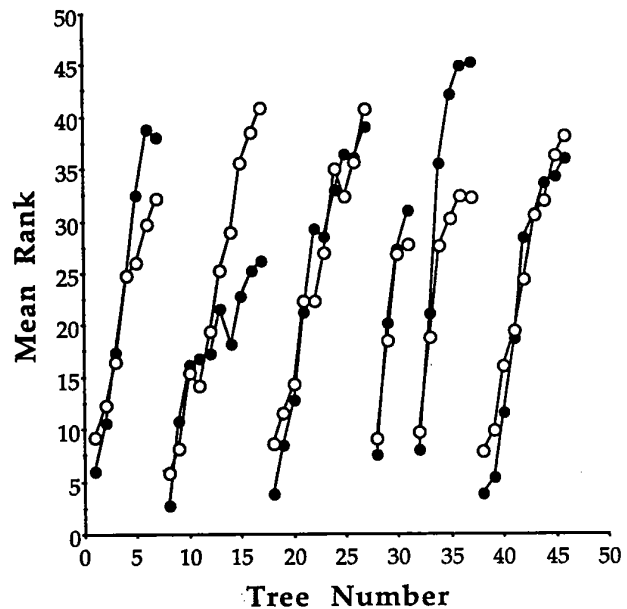


Figure 6. Mean height and size ranks for each of 46 trees plotted left to right by increasing growth order within architectures. From left to right, architectures are H, P, C, D, M, and V. Mean height ranks = open circles; mean size ranks = filled circles.

to ranks within each observer across the 46 trees judged (excluding Architecture L). The mean ranks computed across observers for each tree (arranged by growth order within each architecture) are provided in Figure 6. Size and height judgments were different for Architectures P and M, in particular. M was judged to be greater in size than in height, whereas P was judged smaller. This observation was confirmed when we performed a mixed design randomization analysis with judgment type and architecture as factors (Edgington, 1990; Manly, 1991). Using 5,000 randomizations, we found that architecture,  $F(5, 230) = 24.9, p < .001$ , and the interaction,  $F(5, 230) = 11.5, p < .001$ , were significant, and judgment type was not ( $p > .1$ ).

Estimates of size were different from those of height. What aspect of tree form was used to make judgments about size? In the instructions, we asked observers to take into account the increasing length of trunks and branches, irrespective of their orientation to the vertical. We computed the longest length traversable within each simulated tree from trunk base to branch tip. In a central trunk tree, this corresponded to the height of the tree. In trees with trunks growing at an angle to the vertical, this length was greater than the height of the tree. We divided this length by  $H$  to map it into tree images. (We mapped to the images by dividing by  $H$  rather than by the simulated distance to the tree because we had held image height constant. Thus, if the image height was set to 1, for mathematical convenience, then the mapping of tree height,  $H$ , to image height,  $H_i$ , was  $H/H_i = 1 = H_i$ .)  $L/H$  also serves as an index of the outward growth of a tree, or its lateral spread. If one considers  $L$  as the hypotenuse of a right triangle



formed by the trunk of a tree,  $H$  is the height and the spread is the base.

When we performed a multiple regression regressing mean size judgments on  $N^5$  and  $L/H$ , the result was significant ( $p < .001$ ) and accounted for 91% of the variance. The two factors contributed equally to the regression as shown by their respective beta weights (for  $N^5$ ,  $p < .001$ ,  $\beta = 0.72$ , partial  $F = 244.1$ , and for  $L/H$ ,  $p < .001$ ,  $\beta = 0.58$ , partial  $F = 159.5$ ). When the analysis was performed using  $H/D$  in place of  $L/H$ , the  $r^2$  was only .76. When we performed the analysis including both  $H/D$  and  $L/H$ , only the latter was significant. (When this analysis was performed on height judgments from Experiment 1, only  $H/D$  was significant with  $\beta = -.76$  as opposed to a  $\beta$  of  $-.04$  for  $L/H$ .)

The implication of these results was that observers were able to assess different scale properties of trees using different aspects of tree form preserved in their images. Observers did not base their estimates of tree size on the amount of wood in a tree, but rather on the amount of lateral spreading. We computed the amount of spread as the radius of the area along the ground covered by tree branches. When this was regressed on mean size judgments, the result was significant,  $F(1, 44) = 297.6$ ,  $p < .001$ , and accounted for 87% of the variance. The two types of judgment, height and size, thus seemed to have been literally of orthogonal properties, one of vertical extent and the other of horizontal extent.

### Experiment 3: Conferring a Metric on Ground Texture Gradients

The obvious problem with the simulation results in Experiment 1 was that, although the judgments were well ordered, the slopes were shallow and the random errors in estimates were substantial. Mean estimates did not exceed 50 ft, whereas modeled heights reached 90 ft. Why should this have been so?

To address this problem, we compared and analyzed judgments of real trees versus simulations. There were a number of differences between the respective viewing conditions. Viewing real trees involved a ground texture gradient as well as binocular and wide-angle vision, upright posture, and (potentially) optical transformations from either tree or observer motion. In contrast, to investigate tree form as information, we had isolated simulated tree forms in flat pictorial displays that did not admit wide-angle vision or transformations from either tree or observer motion or from binocular vision. Isolation meant that tree forms did not appear in the context of a ground texture gradient.

The potential significance of the ground texture gradient was that observers could use the perceived size of the real trees to scale the ground texture elements. The continuous ground texture, in turn, might have provided a basis for comparison among trees. As shown in Figures 1h and 4c, observers of simulated trees were unable to discriminate architectural differences in the relation between  $H/D$  and tree height. Also, as indicated by random local reversals or flattening in individual judgment curves, observers had

difficulty in resolving successive increments in  $H/D$  or the number of branches. Placing simulated trees appropriately within a ground texture gradient would provide another dimension along which variations might be resolved.

More important, ground texture would provide a common substrate in which the scale from the trees could be invested. The scaling of this substrate could be fine tuned and adjusted over subsequent exposures to a variety of trees. In this way, for instance, observers might discriminate architectural variations in the scaling relations. This possibility would have more general relevance. Our generation of simulated tree forms was strictly deterministic, but actual tree forms are subject to stochastic variations. For instance, the coefficient in the diameter to height relation can vary depending on whether a tree is competing in a forest stand or is growing in the open under less stressful conditions (McMahon, 1975; McMahon & Kronauer, 1976). It can also vary with the type of wood (Wilson & Archer, 1979). Ultimately, architecture can affect the coefficient in the relation determining branch number (Fisher & Honda, 1979a, 1979b; Honda et al., 1981). Additionally, growth varies with climate, including average temperature and annual rainfall. Given these and other variations, detection of regularity over a number of trees appearing in the context of a single visual environment would be a prerequisite for stable, reliable, and more accurate perception of scale.

### *Scaling of Ground Texture Gradients*

An optical texture gradient projected from the ground provides a relation between objects at different locations. However, the scaling on that relation is relative. Assuming that the texture elements along the ground are invariant in size, the optical texture elements can be used to scale the relative sizes of objects in two closely related ways. Either object image size can be compared with the image size of neighboring texture elements, or the number of optical texture elements occluded by different objects can be compared. In these ways, the viewer can determine that one object is larger than or farther away than another object, but the actual sizes of objects cannot be determined without additional information.

A scale-specific quantity can be used to impart definite scale to the field. Our question was whether trees might confer a metric on ground texture gradients. If the sizes of trees located at various places within the gradient can be determined, then the scale of the ground texture elements might be established by comparison. The scale of other nonbiological objects appearing within the gradient might be determined in turn. We investigated whether the trees could be used, in the context of a ground texture gradient, to scale the size of objects with Platonic rather than biological forms. We placed seven cylinders at various locations within a single gradient. Cylinder size was varied to preserve image size. Observers judged cylinder heights after having judged the heights of trees appropriately placed at various locations within the gradient.

### The Horizon Ratio Hypothesis

By including ground texture with a horizon, we may have introduced information about scale other than the relative scale of the gradient or the definite scale hypothetically provided by tree images. Optical information associated with the observer's eye height has been hypothesized as a source of scaling (Gibson, 1979; Lee, 1980; Mark, 1987; Sedgwick, 1980; Warren, 1984; Warren & Whang, 1987). On a flat ground plane, the image of the horizon has been shown to intersect the images of all objects in the field of view at the height of the point of observation. The ratio of the total image height to the height of the point of intersection with the horizon in the image would determine the total actual height if the eye height were known. Use of eye height with the horizon ratio is analogous to the use of the distance between the two eyes as a source of scale in binocular convergence. The distance between the viewer's eyes has been hypothesized as a source of scale because of its stability and invariance.

The eye height hypothesis is controversial, however, because eye height does not remain invariant as observers alter either their posture or the heights of the surfaces on which they rest (Bingham, 1988). Eye height varies continuously as an observer adjusts from standing upright one minute, to kneeling or sitting the next, or as an observer locomotes along a trench, over a hill or up a set of stairs. Studies using the eye level hypothesis assume that eye height is equal to some constant proportion of the observer's height. On the basis of that assumption, the perceived sizes and distances in the surround would alter continuously with changes in eye level. If this were true, perceived sizes would double whenever the observer's eye height is reduced by 50% (by crouching, for example). As an alternative, the assumed eye level value might be adjusted in these situations on the basis of yet additional information about the current eye level. Unfortunately, this strategy introduces a highly undesirable regress. Nevertheless, there is evidence to support the horizon ratio hypothesis (Carello, Groszofsky, Reichel, Solomon, & Turvey, 1989; Mark, 1987; Rogers & Costall, 1983; Warren, 1984; Warren & Whang, 1987), and by including ground texture gradients in our displays, we introduced the possibility that observers might use the horizon ratio to scale their judgments of height.

We controlled for the use of the horizon ratio by asking a separate group of observers to judge the size of cylinders appearing in the context of the ground texture gradient without viewing or judging trees. If the horizon ratio was the source of any observed improvements in the accuracy of judgments made of simulated trees with ground texture gradients, then similar results should have been obtained for judgments of cylinders viewed either with or without trees.

A final inadequacy of the simulations used in Experiment 1 was that the tree images were produced using parallel projection for all sizes and distances, even though this was inappropriate for small trees that were closer to the viewer. As a result, the images were all extremely flat and, for nearer trees, distorted. For Experiment 3, we used polar projection in addition to placing the trees in the context of a ground texture gradient. Sample images of increasingly large trees

in architecture C appear in Figure 7. (These should be compared with the images in Figure 1.)

In these ways, we sought to make simulations more comparable to natural viewing conditions. However, we also manipulated conditions to make the viewing of real trees more comparable to the simulations. Information derived from wide-angle and binocular vision was eliminated by having observers view trees through a tube with an aperture of visual angle ( $\approx 40^\circ$ ) slightly larger than that of the trees. Although a proportion of the ground extending from the observer to the tree was occluded, some ground texture immediately around a given tree remained visible. Finally, we asked observers to judge the height of the real trees in photographs taken at the original viewing locations from about the same visual angle as that provided by the tube.

### Method

**Participants.** Twenty students at Indiana University participated in judging simulated trees with ground texture gradients. In exchange for their participation, they received credit in an introductory psychology course. Sixteen students participated in judging real trees observed through a tube, and 16 students participated in judging photographs of real trees; they were paid at \$4.25 an hour. In all cases, half of the participants were men and half were women. All had normal or corrected-to-normal vision.

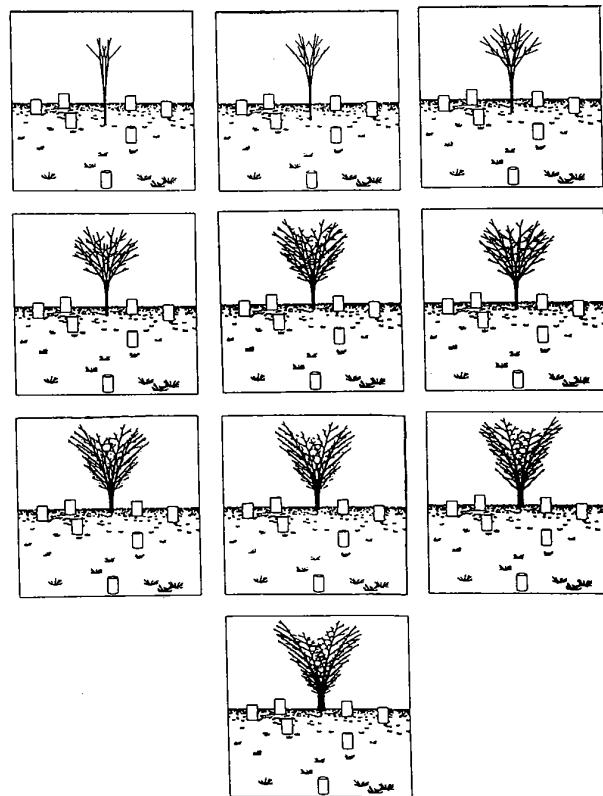


Figure 7. Images used in Experiment 3 of successively taller trees over 10 orders of growth in Architecture C.

*Display generation.* Simulated tree images were generated in the same way as for Experiment 1, with the following exceptions. Only six different architectures were used, excluding Architecture L. All tree silhouettes were placed in the same ground texture gradient. Ground texture elements resembled crabgrass. Distances between the trees preserved tree image height at 10° visual angle for a point of observation located 1.7 m above the ground. Tree branches and trunks of circular cross-section were generated in three-dimensional space, enabling us to use polar projection to images. Seven cylinders of heights ranging from 1 ft to 10 ft (0.3 m to 3.0 m) were placed at various locations along the ground such that image size was preserved. As illustrated in Figure 7, the layout of both texture elements and cylinders was the same in all images, whereas trees were placed at various distances along the midline of the image.

A 35-mm camera with a 50-mm lens was used to take black-and-white photographs of the 16 trees on the campus. The trees were photographed without leaves. Portions of buildings and other trees and shrubs appeared in the background of all photographs. Photographing was done on a cloudy day to minimize shadows and maximize contrast. The photographs were taken in the locations used in all experiments that involved real trees. The viewing angle was just slightly larger than the image height of the trees. High-contrast 7 in. × 5 in. (17.8 cm × 12.7 cm) glossy prints were used.

*Procedure.* The procedure used to estimate the size of the simulations was identical to that used in Experiment 1, with a single exception. As before, observers first judged the heights of 16 real trees on the Indiana University campus and then judged the height of simulated trees. After having judged the 46 simulated tree images, they were asked to judge the heights of the cylinders that had appeared in all of the tree images. Observers were allowed to examine the packet of tree images a second time, examining the cylinders in the context of the different trees. They were shown an image of the cylinders (and texture gradient without trees) in which the cylinders were randomly labeled 1 to 7, and used these labels to refer to cylinders when writing their estimates on a protocol sheet.

The procedure used to estimate the sizes of 16 real trees as seen through the tube was very similar to that described in Experiment 1 for judging real trees. Observers were instructed to keep their eyes to the ground until they were positioned for judging a tree and the tree was pointed out to them. In this experiment, however, they were asked to close their nondominant eye and to hold a 3-in. (17.62-cm) black cardboard tube up to their other eye before raising their head to view a given tree. Before raising their heads, the observers also closed the eye used with the tube and kept it closed until the tube was directed at the tree. The experimenter assisted them in orienting correctly to the tree. They were asked to give their estimates of tree sizes within 2–3 s of opening their eye. These observers did not subsequently judge simulated trees.

The procedure for judgments of photographs and of simulated cylinders without trees were the same as those for judging simulated trees, with the following exceptions. Observers first judged a set of 10 real trees (different from the 16 trees to be judged in photos), then returned to the laboratory and judged the sizes of 16 real trees in photographs arranged in the same random orders used previously with other observers who had viewed the trees outdoors. After observers had completed these judgments, they were asked to judge the heights of simulated cylinders. They were shown the image of cylinders and texture gradient without trees. Aside from the inability to flip through simulated tree images, the procedure was the same as used for cylinders with trees.

Observers in all three conditions (binocular viewing, through-the-tube, and photographs) judged the same 16 trees as were used in Experiment 1.

## Results and Discussion

Both systematic and random errors were lower for simulated trees than they had been in Experiment 1. A ceiling on maximum judged heights was still apparent, although it was slightly higher than that obtained in Experiment 1. In judgments of real trees, systematic and random errors increased with increasingly restrictive viewing. Maximum judged heights decreased when binocular and wide-angle vision were eliminated. Finally, the number of systematic and random errors was substantially larger in estimates of cylinders judged alone than for those judged in the presence of trees.

*Judgments of simulated trees.* When mean judged heights were regressed linearly on modeled heights, both the slope (0.50) and the  $r^2$  (.93) were greater than those in Experiment 1, whereas the intercept (11.4) was essentially the same. The  $r^2$  obtained when this regression was performed on all individual judgments was .40. In regressions performed separately for each observer, the mean  $r^2$  was .75 ( $SD = .10$ ). These  $r^2$ s also were greater than in Experiment 1. We performed an ANOVA comparing the slopes for individual observers in Experiments 1 and 3. The result was significant,  $F(1, 42) = 4.06, p < .05$ . A similar ANOVA on individual  $r^2$ s was also significant,  $F(1, 42) = 30.7, p < .001$ . When we regressed judged heights from Experiments 1 and 3 on modeled height with vectors coding for experiment and the interaction, the result was significant,  $F(3, 2020) = 346.9, p < .001, r^2 = .34$ . Modeled height was significant,  $\beta = 0.55$ , partial  $F = 934.2, p < .001$ . Although experiment was not significant ( $\beta = 0.05$ ), the interaction was significant (partial  $F = 12.7, \beta = 0.15, p < .001$ ), indicating that the slopes were different, but not the intercepts. These analyses show that inclusion of the ground texture gradient produced less random error and an increase in mean judgments of larger trees. Overall, as predicted, observers were better able to resolve changes in tree form and, therefore, changes in size.

However, as shown in Figure 8, the result of a linear fit was somewhat misleading. Mean judgments were linear and close to actual values for modeled heights up to about 40 ft (12.19 m), at which point judgment curves veered off as if approaching a ceiling. We performed separate regressions using mean judgments for each architecture within the linear range. Table 1 shows that for four of the six architectures, the  $r^2$ s were all .98 or better and the slopes were all above .7 and intercepts less than 5. Nevertheless, a second-order polynomial regression performed using all mean judgments was significant,  $r^2 = .94, F(2, 43) = 352.8, p < .001$ , and the second-order term was significant ( $p < .01$ ). Implicit in this polynomial fit was a maximum value at ceiling. When we took the derivative of the regression equation and set it equal to 0 to find the locus of the maximum, the resulting value was 126.7 ft (38.62 m). This was only 5 ft (1.52 m) less than the maximum height used in our model. However, when we substituted this back into the polynomial equation to find the predicted mean judgment, the result was only 55 ft (16.76 m), reflecting the compression evident in Figure 8.

When we performed polynomial fits separately for each architecture, the locus of the maximum was different in each

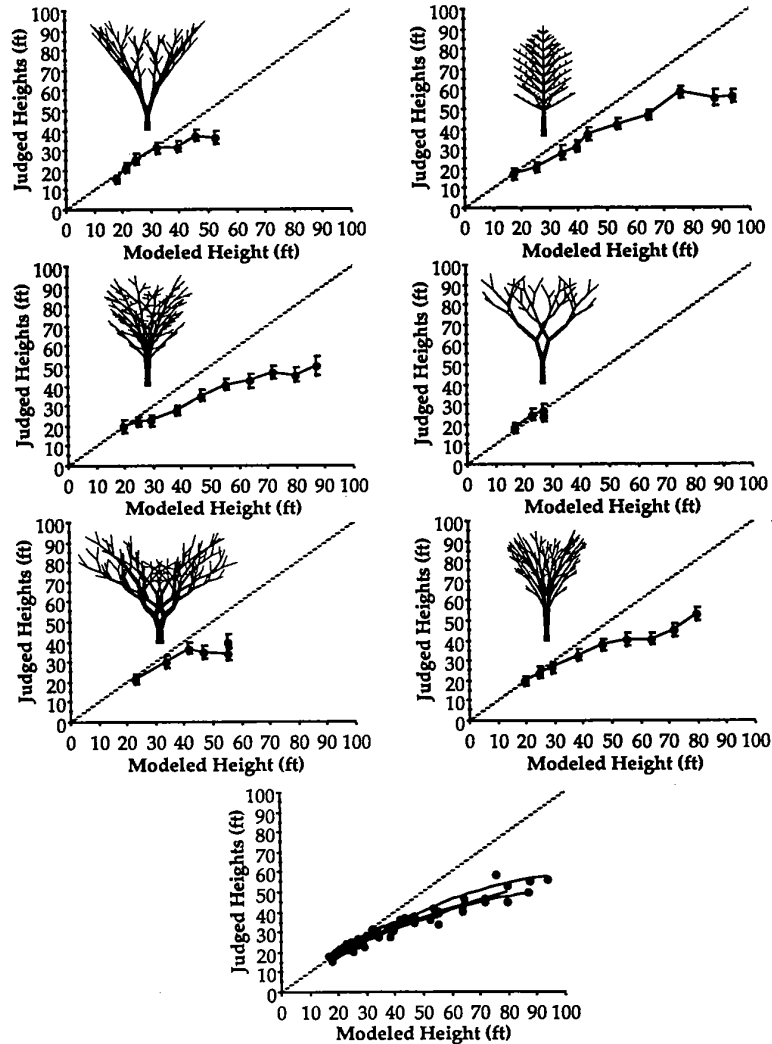


Figure 8. Experiment 3: Mean height estimates (with standard error bars) plotted against modeled heights for each of six architectures. Images of mid-range trees also are shown for each architecture. Proceeding from left to right and top to bottom (with standard errors in feet of the average deviations of judged height from modeled height for each architecture): (a) Architecture H (1.11 ft); (b) Architecture P (1.24 ft); (c) Architecture C (1.31 ft); (d) Architecture D (1.13 ft); (e) Architecture M (1.65 ft); (f) Architecture V (1.21 ft); (g) means for all six architectures plotted together, each with a least-squares best fit second-order polynomial curve. The stippled diagonal in each plot is a line of slope 1, intercept 0.

case. This accorded with our intuitions in generating different simulated maximum heights for the different architectures. The maxima (and corresponding predicted mean judgments) were as follows: for H, 50.1 ft (37.1 ft); for P, 113.1 ft (60.8 ft); for C, 137.8 ft (60.7 ft); for D, 26.5 ft (25.7 ft); for M, 52.4 ft (37.1 ft); and for V, 165.8 ft (63.7 ft).<sup>3</sup> The maxima for Architectures D and M occurred at almost exactly the values at which these trees stopped growing upward and only continued growing outward. The difference between the modeled heights at the maxima and the predicted judgments reflected the compression in judgments. These points also

were fitted well by a second-order polynomial ( $r^2 = .99$ ,  $p < .001$ ) with a significant second-order term ( $p < .02$ ) and a maximum occurring at 67.6 ft.

We turned next to an analysis of the hypothesized sources of information. The results of regressions of mean judgments

<sup>3</sup> The metric equivalents of these judgments are as follows: for H, 15.27 m (11.3 m); for P, 34.5 m (18.5 m); for C, 42.0 m (18.5 m); for D, 8.08 m (7.8 m), for M, 16.0 m (11.3 m); and for V, 50.5 m (19.4 m).

Table 1  
*Linear Regressions on Mean Judgments by Architecture for Modeled Heights Below 40'*

Architecture	Slope	Intercept	$r^2$
H	1.06	-1.6	.98
P	.70	4.4	.99
C	.54	8.7	.98
D	.91	3.5	.99
M	.82	2.8	.99
V	.58	9.6	.99

on  $H/D$  and  $N^5$  are shown in Figures 4e and 4f. The maximum height of 64 ft indicated by the intercept of the relation between  $H/D$  and judged height was 10 ft greater than that in Experiment 1, but still considerably below that for modeled heights as shown in Figure 4a. This value was close to that derived through the polynomial fits given above. The scaling of judgments with the number of branches reflected a surface law, as in Experiment 1. When mean judgments were regressed simultaneously on  $H/D$  and  $N^5$ , the result was significant,  $r^2 = .84$ ,  $p < .001$ . Only  $N^5$  was significant, partial  $F = 34.7$ ,  $\beta = 0.81$ ,  $p < .001$ . The beta for  $H/D$  was  $-0.11$ . This reproduced the pattern that resulted when this regression was performed on modeled heights, in which the betas were 0.84 and  $-0.12$ , respectively.

The relation between  $H/D$  and modeled height exhibited different slopes and intercepts for different architectures depending largely on the orientation of the trunks with respect to the vertical. In Experiment 1, observers were unable to discriminate these architectural differences, as indicated in Figure 4c. In contrast, observers in Experiment 3 were able to detect these differences, as indicated in Figure 4e. The differences found in Experiment 3 mirrored those for modeled heights indicated in Figure 4a. When slopes for each architecture of the relation between  $H/D$  and mean judgments from Experiment 3 were regressed on slopes derived for each architecture using modeled heights, the result was significant ( $r^2 = .85$ ,  $p < .03$ ), with a slope of .6. A similar result was obtained using intercepts. In the same comparisons using data from Experiment 1, the results were not significant and the slope (of the relation between slopes) was flat. Thus, the scaling relation between the  $H/D$  ratio and judged heights was different for different architectures in Experiment 3, but not in Experiment 1. In Experiment 1, the failure to discriminate architectural differences was also reflected in systematic errors in judged heights. This is shown in Figure 1h by a diversity of slopes for the architectures. In Experiment 3, the successful discrimination of architectural differences was reflected in parallel judgments of height for different architectures, as shown in Figure 8g. The implication of these results was that the presence of the ground texture gradient allowed observers to discern architectural differences in the scaling information and to make more accurate estimates of height.

We had expected that the ground texture gradient would allow observers to better resolve the scaling information obtained in apprehension of individual trees. In each instance, the scaling information could be mapped to the texture gradient with a gradual tuning of the gradient over successive

trees. To investigate this possibility further, we examined the pattern over presentation order of mean percentage of error in the initial set of judgments. We computed the mean percentage of error for each trial across observers, including observers who judged different presentation orders. For instance, all errors for the first tree presented were averaged even though this involved trees of different size. When we examined a scatterplot of mean percentage of error against order of presentation, a decreasing trend was apparent. A second-order polynomial regression was significant,  $r^2 = .30$ ,  $F(2, 43) = 9.07$ ,  $p < .001$ , with a significant second-order term ( $p < .05$ ). The equation described mean percentage of error as starting at 37% at Trial 1 and descending to 13% over 35 trials. That is, the mean percentage of error dropped to 65% of its initial value. The majority of the improvement occurred in early trials. Two thirds of the drop had occurred by Trial 15. In contrast, a similar scatterplot using the data from Experiment 1 exhibited no such trend. A linear regression was not significant ( $r^2 = .05$ ), and the slope was flat. These results implied that the presence of the texture gradient enabled observers to improve the accuracy of their estimates over trials.

*Size estimates of real trees.* We next compared simulation results to size estimates of real trees. The results indicated that the compression exhibited by judgments of simulated trees was produced by the viewing conditions, that is, monocular viewing without wide-angle vision.

There were leaves on the 16 trees at the time that they were judged in Experiment 1. This was not true of Experiment 3. However, as shown in Figures 3a and 3b, the results were essentially the same. When height estimates of trees without leaves were regressed linearly on actual heights, the slope was .94, the intercept was  $-1.13$ , and the  $r^2$  was .80, as compared to .93, .59, and .82, respectively, with leaves. The mean  $r^2$  for separate regressions performed on the data for each observer was .89 ( $SD = .04$ ) without leaves as compared with .91 ( $SD = .06$ ) with leaves. As shown in Table 2, when these analyses were performed on the data for trees seen through a tube and in photographs, the slopes and  $r^2$ s dropped progressively, and the intercepts increased to values that were comparable to those obtained in judgments of simulations. We performed multiple regressions on the data from these successive viewing conditions (binocular, through-the-tube, and photographs), taking two at a time, using modeled height and vectors coding for viewing condition and the interaction. In each instance, the slope and intercept differences were significant.

A drop in the ceiling for maximum judged heights is apparent in Figure 3. Second-order polynomial fits were sig-

Table 2  
*Linear Regressions for Judgments of Real Trees in Four Viewing Conditions*

Viewing condition	Slope	Intercept	$r^2$	$m$	$SD$
With leaves	.93	.59	.82	0.91	0.06
Without leaves	.94	-1.13	.80	0.89	0.04
Through the tube	.75	3.72	.69	0.82	0.10
Photographs	.59	8.37	.62	0.72	0.07

nificant ( $p < .001$ ) in all cases. However, the second-order term was not significant for trees without leaves. The predicted mean judgments at the maxima were 105 ft (32 m) for trees with leaves, 61 ft (18.59 m) for trees viewed through a tube, and 51 ft (15.54 m) for photographs. When mean height judgments for real trees were regressed on measured  $H/D$  ratios, the intercepts indicating maximum tree heights dropped from 93 ft (28.35 m) for trees without leaves, to 87 ft (26.52 m) for through-the-tube viewing, to 76 ft (23.16 m) for photographs.

**Judgments of cylinders.** As shown in Figures 9a and 9b, both the systematic and random errors were much greater in judgments of cylinder heights performed without seeing trees than with trees. In both cases, the judgments of individual observers were well ordered. The mean individual  $r^2$ s were comparable in both cases, .78 ( $SD = .29$ ) without trees and .81 ( $SD = .23$ ) with trees. However, the variability in slopes and intercepts was much greater in judgments made without trees. The standard deviation for mean individual slopes was 1.15 without trees as compared with .54 with trees. For mean intercepts, the standard deviation was 7.50 without trees compared with 1.96 with trees. When judgments made without trees were regressed linearly on modeled heights, the result was significant ( $p < .003$ , slope = 0.92, intercept = 3.25), but the  $r^2$  was only .08. When the regression was performed using judgments made with trees, the result was also significant ( $p < .001$ , slope = 0.68, intercept = 2.40), with an  $r^2$  of .35.

Presuming that observers were, on average, able to scale the gradient accurately on the basis of tree estimates, we would have expected the slope of the cylinder judgments to be near 1 with a 0 intercept. The slope of .68 was somewhat low. Slope less than 1 was produced by accurate mean estimates of the taller cylinders coupled with overestimation of the shortest cylinders. The smallest cylinder was 1 ft (.30 m) in height. Observers expressed their judgments in feet. The lowest estimates were of 1 ft, and these occurred only for the smallest cylinder. We inferred from this that the low slope was the result of a floor effect.

We noted that a couple of the observers in the condition without trees were surprisingly accurate as compared with other participants. These observers produced slopes and intercepts near 1 (as well as an  $r^2$  of .99). We also noted that whereas most of the observers expressed some perplexity and dissatisfaction with the task, these observers did not. We asked these observers how they had performed the task. They explained that they had used the scale determined by the ground texture elements, which they had assumed to be overgrown grass. When interviewed, other observers said they had just guessed and that they had not identified the ground texture as grass. Although they were of the appropriate scale, the simulated ground texture elements were only vaguely intended to be like grass. Nevertheless, the results without trees were perhaps somewhat better than they might have been had we used an entirely arbitrary or unnatural ground texture element, for instance, dots or a grid.

Whether or not trees were present, estimates of cylinder sizes were well ordered, as would be expected given the relative scaling allowed by ground texture gradients. How-

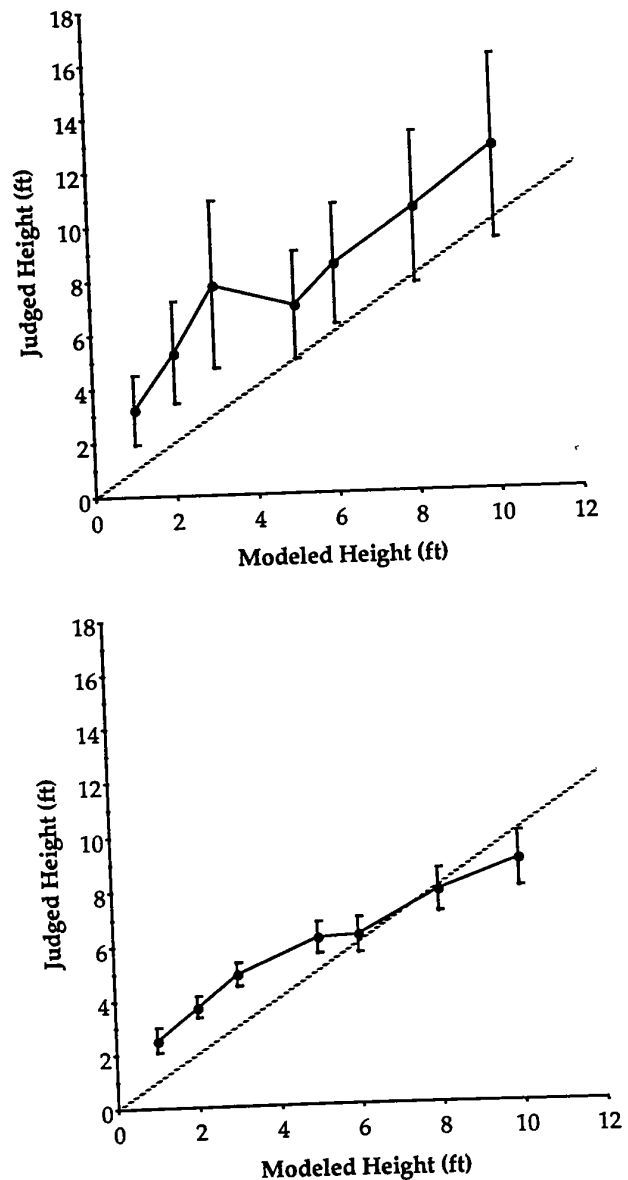


Figure 9. Mean height estimates of cylinders (with standard error bars) plotted against modeled heights. Top: Cylinders viewed without simulated trees. Bottom: Cylinders viewed in presence of simulated trees. The stippled diagonal in each plot is a line of slope 1, intercept 0.

ever, judgments of cylinders alone were subject to considerable random variability, whereas judgments of images that included trees were well constrained and much more accurate. The results indicated that apprehension of the trees enabled observers to scale both the ground texture gradient and other nonbiological objects appearing in the context of that gradient and that the inclusion of a ground texture gradient with a horizon did not lead to the use of the horizon ratio with an assumed eye height.

#### Experiment 4: Controlling for Practice and the Horizon Ratio

In Experiment 3, observers who judged cylinders without seeing the simulated trees only saw the texture gradient and cylinders once, whereas observers who judged cylinders with trees saw the gradient and cylinders together with 46 different trees. Perhaps repeated viewing yielded reductions in random error in cylinder judgments as a practice effect. To control for this possibility we ran another experiment in which observers judged the cylinders after having judged the heights of 52 poles that appeared in silhouette on the texture gradient with the cylinders. This also provided us with another test of the potential use of the horizon ratio to judge heights. The poles appeared in images exactly as had the trees. The image heights were the same, and the actual heights spanned the same range as the trees. Four different pole thicknesses were used at each of 13 different heights with thicknesses equal to between .02 and .08 of actual height. The cylinders and texture gradient were the same as shown in Figure 7.

#### Method

**Participants.** Fifteen students (7 men and 8 women) at Indiana University participated in the study. All had normal or corrected-to-normal vision. Participants were paid at \$4.25 an hour.

**Procedure.** Participants judged the heights of the poles and then the heights of the cylinders. The instructions and procedures were the same as used with the tree simulations in Experiment 3.

#### Results and Discussion

Judgments of pole heights were fairly well ordered, but the variability was extreme. Judgments were regressed linearly on actual pole heights separately for each observer. The mean  $r^2$  was .49 ( $SD = 0.33$ ), the mean slope was .38 ( $SD = 0.47$ ), and the mean intercept was 27.9 ( $SD = 63.5$ ). The most striking variability was in intercepts. This reflected the fact that different observers expressed judgments in units of inches or yards as well as feet. (Although we had suggested that estimates be expressed in feet, we had always allowed observers to use other units as long as they were clearly indicated, to allow observers accustomed to SI units to express judgments in meters. This was the first time observers had taken advantage of this opportunity to use yards or inches.) When a regression was performed on the collected data, the result was significant,  $F(1, 778) = 14.0, p < .001$ , but the  $r^2$  was only .02. As shown in Figure 10a, mean judgments overestimated shorter heights and underestimated taller heights. Given the size of the objects, however, standard error bars were more representative of performance (cf. Figure 8b).

Results of trials involving the use of cylinders were similar to those using poles. The mean  $r^2$  was .48 ( $SD = .42$ ), the mean slope was .61 ( $SD = 1.17$ ), and the mean intercept was 4.8 ( $SD = 14.6$ ). These results were comparable to those previously obtained for size estimates of cylinders without

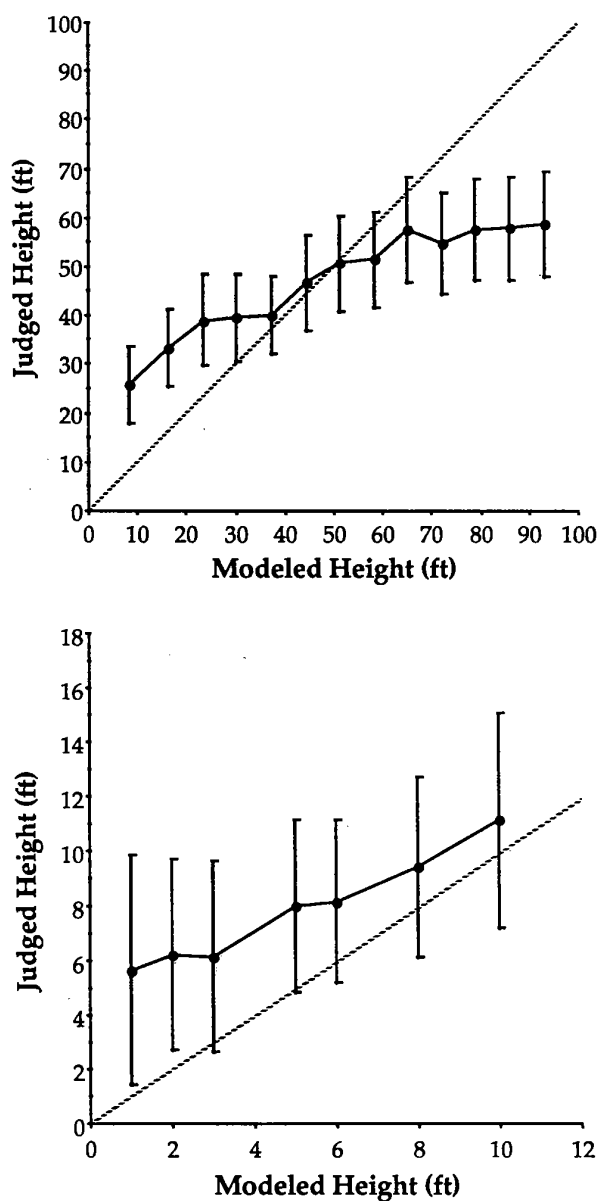


Figure 10. Mean height judgments (with standard error bars) from Experiment 4 plotted against modeled heights. Top: poles. Bottom: cylinders. The stippled diagonal in each plot is a line of slope 1, intercept 0.

trees, although the current results were even more variable. The result of a linear regression of judgments on actual heights was not significant,  $F(1, 96) = 2.0, p > .05$ , with an  $r^2$  as low as that for the pole judgments. As shown in Figure 10b, the standard error bars overwhelmed the means. This figure should be compared with Figures 9a and 9b.

These results showed that practice had nothing to do with the more accurate assessment of cylinder size that was obtained when observers could compare the cylinders to tree

images. Furthermore, the addition of a horizon with the texture gradient used in Experiment 3 does not account for the resulting improvements in performance. The only source of definite scaling information in the simulations of Experiment 3 was the tree forms.

### General Discussion

We have demonstrated that the forms of biological objects can provide visual information for the scale of the surroundings. Texture gradients, by themselves, provide information only about the relative sizes of objects. We found that trees placed within a gradient conferred a metric on the field. This enabled observers to estimate the size of nonbiological objects appearing in the context of the same ground texture gradient.

Use of form as information about scale is parsimonious because it reduces the scaling problem to an identification problem (Bingham, 1987a, 1988). In visual perception, the scaling problem is created by the fact that metrics associated with spatial (and mass-related) dimensions are lost in the mapping from objects and events into optical pattern (e.g., Turvey, 1977). Only temporal metrics are preserved. For instance, the period of an optical transformation can be measured in seconds, but optical velocities cannot be measured in meters per second. Nevertheless, many qualitative properties of objects and events are preserved in the mapping to optical pattern (e.g., Bingham, 1987a, in press-a; Bingham, Rosenblum, & Schmidt, 1991; Koenderink, 1986, 1990; Koenderink & van Doorn, 1978; Todd & Reichel, 1989).<sup>4</sup> The scaling required for these qualitative properties is somewhere between ordinal and interval, but not ratio or absolute. Nevertheless, if the size of objects and events determines their forms or qualitative properties, then weaker types of scaling on mappings to optical properties may suffice to provide information about size. Given the nature of these mappings, this type of solution may be the only viable alternative.

We note also that this solution becomes particularly powerful when extended to events and kinematic form. Kinematic form includes the time dimension and can be described in terms of the forms of trajectories in either phase space or event space (Bingham, 1987a, 1987b, 1988, in press-a). The analysis is strictly analogous to that described in this article because the forms of trajectories are determined by the scale of the underlying spatial and physical dimensions (Bingham, in press-a; Muchisky & Bingham, 1992; Bingham et al., 1991). The possibility is especially significant because it extends this solution beyond the biological domain to events in general. For instance, Muchisky and Bingham (1992) have obtained results indicating that the forms of various inanimate events that involve free fall map into optical forms that can be used to determine the sizes of objects in the events. Thus, when properly extended, the solution to the scaling problem developed in this article may prove fruitful.

### *Relative Versus "Absolute" or Definite Scaling*

Relative scale, as determined by a texture gradient, for example, allows an observer to determine that one object is

larger or farther away than another, but not that one is 6 ft (1.83 m) tall at a distance of 20 ft (6.09 m) and the other 3 ft (.91 m) tall at a distance of 10 ft (3.05 m). Such determinations require "absolute" scaling. Some 25 years ago, the possibility that familiar size enabled estimation of absolute size became controversial. Ultimately, as reviewed in Epstein (1967), the controversy was resolved in favor of absolute size perception by means of familiar size, but the resolution entailed refinements in method.

The difficulty has been described succinctly by Gogel (1977, pp. 140–141) using the following example. To test the apprehension of distance, observers are shown a luminous square placed in a dark field at one of two distances, either 3 m or 6 m. Half of the observers judge the 6-m distance first and the remaining half judge the 3-m distance first. If observers are unable to apprehend the "absolute" distance (and/or size) of the square, then on the first trial, the two groups of observers will judge the two distances as the same on average, for instance, as 2 m. Next, the use of relative scaling information means that the judgments on the second trial will be determined by the relative change in projected size of the square. A first group that first judged the square at 6 m as being 2 m away, will now judge the square at 3 m as being 1 m away. Halving the distance should bring size estimates down by 50%. The second group, having judged the 3 m distance as being 2 m away, should now judge the 6 m distance as being 4 m away. The relative proportions in each instance should be determined by the relative changes in projected size. When the judgments of the two groups are averaged, the resulting means are 1.5 m and 3 m. Gogel suggested that these means might be interpreted erroneously as evidence for the perception of absolute distance based on the absolute size of the retinal image, when in fact only relative scaling was involved.

We used the data from Experiment 3 to investigate the possibility that mean estimates of tree height might have been derived as envisioned by Gogel (1977). We had used three different presentation orders for each of three different groups of observers. The first trial in each involved a different size tree of Architecture H. The small, medium, and large sizes spanned nearly the full range of modeled heights for this architecture. We performed a simple linear regression on this first trial data, regressing judged heights on modeled heights. The result was significant,  $F(1, 18) = 5.20$ ,  $p < .03$ ,  $r^2 = .23$ , with a slope of .41 and an intercept of 9.7 ft. On average, different sizes were not judged as being equal. On the contrary, successively larger trees were judged as larger with the mean judgment of the smallest tree being rather precise. Given the finding that mean judgment accuracy continuously improved over the first 15 trials of Experiment 3 by virtue of the texture gradient, we judged this

<sup>4</sup> Factors that determine biological forms have been used previously in work on visual recognition, but with an emphasis on symmetric shapes (Blum, 1973; Marr, 1982). For instance, Marr (1982) used the symmetry of cylindrical or conical limb segments. So did we. However, following Shaw et al. (1982), our emphasis has been on asymmetric distortions in biological forms that are produced to preserve physical or functional symmetry.



result to be consistent with the general results of Experiment 3. When we repeated this analysis for each of the next 3 trials, the results were significant and comparable in all cases, as shown in Figure 11a. We performed a multiple regression on the data of the first 4 trials, regressing judgments on modeled heights and vectors coding for trial and the interaction. The overall result was significant,  $F(3, 76) = 12.5, p < .001, r^2 = .33$ , but only the modeled height factor was significant (partial  $F = 34.8, p < .001$ ). The slope was 0.42 with an intercept of 9.5. The result was the same when we performed the regression with observer group coded instead of trial.

As a second control for this potential problem, we went into the classrooms of two large sections of an introductory psychology course at Indiana University and gave each student 1 of the 46 tree images from Experiment 3 and asked for an estimate of tree height. Between 7 and 9 students (predominantly female) judged each tree image. Under these conditions, we expected the results to be extremely noisy, and in fact they were. However, as shown in Figure 11b, they were comparable on average to the results for the initial trials in Experiment 3.

Do our results provide evidence that observers are able to perceive the absolute size of trees? The difficulty is that *absolute* sounds so inflexible, as though requiring extreme precision. However, the determination of the accuracy of a measurement is always a function of the way that the information is to be used. The fit required for a wine bottle cork is not very tight if the goal is simply to prevent air exchange and very tight if the goal is to prevent it from being opened by a 2 year old. Although a tolerance that is used to determine accuracy is relative to a functional context, it would not be appropriate to suggest that the scaling of a measurement is, therefore, relative.

Relative scaling is actually the more inflexible or definite notion. If an observer has access only to information strictly about relative scaling but is required to provide metric estimates, then those estimates can vary in principle anywhere from millimeters to light years. The gridlike texture gradient used to illustrate so many textbooks could portray equally well a patchwork of farm fields stretching for miles as seen from a plane, the tiles on a kitchen floor extending for a few feet, or a patchwork of connections on a microchip. As soon as observers are able to provide estimates that are consistently within a marginal tolerance of actual values, the presumption must be that there is information available that is more definite than merely relative scaling. Perhaps absolute is not the best term to use because it does not seem to leave room for the tolerance required for and noise entailed by actual measurement systems. Accordingly, we prefer to refer to *definite scaling*, that is, scaling information that sets the limits on the possible scale. Whether those limits are tight enough to provide sufficiently accurate information is a matter of the intended use for that information. Our evidence does show that tree forms provide definite scaling information that allows determination of the size of trees and surrounding objects.

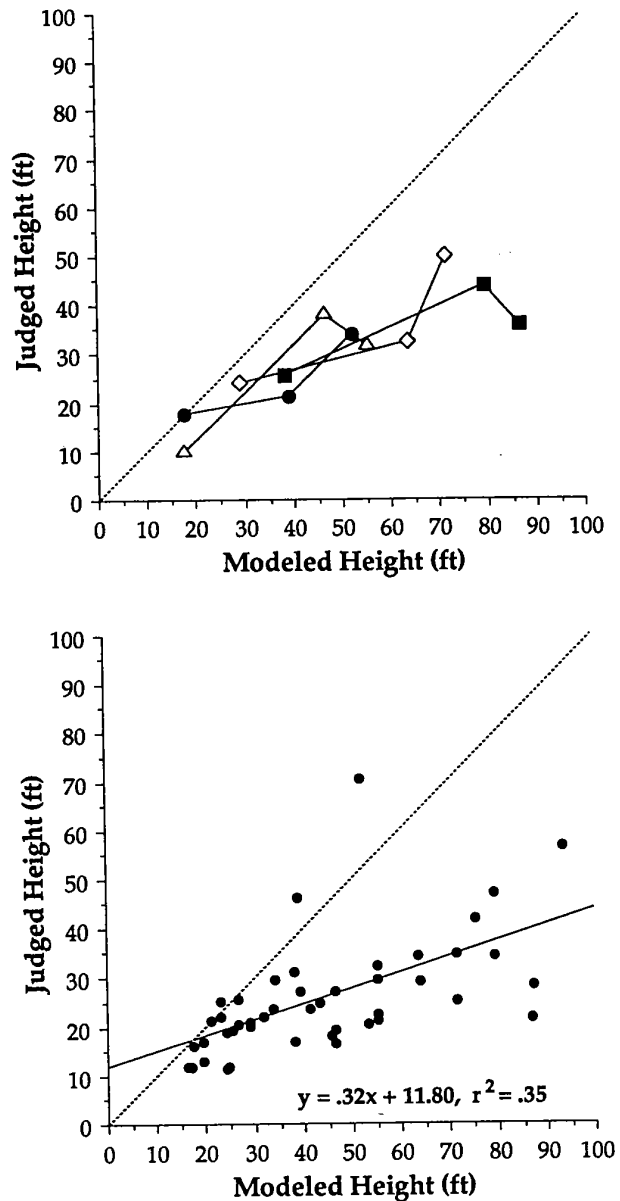


Figure 11. Mean height judgments plotted against modeled heights. Top: Mean judgments from the first four trials of Experiment 3. For each trial, the three means represent the judgments of three groups of observers, each judging a different tree. Trial 1: filled circles. Trial 2: filled squares. Trial 3: open triangles. Trial 4: open diamonds. Bottom: Mean judgments for 46 trees in six architectures with each tree judged by a different group of observers. The result of a simple linear regression is also shown. The stippled diagonal in each plot is a line of slope 1, intercept 0.

#### Complexity of Biological Forms

*Inalienably integrated properties.* We found that different aspects of a biological form could be detected and used to judge different scale properties of biological objects. Ob-

servers used different aspects of tree form to judge either the height or the amount of lateral spread of trees. The properties of form used in the two instances could not be isolated meaningfully from one another in displays. In principle, the strongest correlates of the spread estimates could be captured in stick figure trees, but these would no longer look like actual trees and could as easily be identified perhaps as cracks in pavement. Isolating branch number and branching angles would be similar to manipulating trunk diameter without changing the number of branches. We found that observers balked at judging the latter type of display. Number of branches and relative diameter covary in nature as functionally interactive components of tree growth (E. D. Ford et al., 1990; R. Ford & Ford, 1990). To decouple them would provide contradictory information. Such displays simultaneously specify growth and lack of growth.

The fact that estimates of tree height and spread covaried principally with alternative aspects of tree form did not mean that the remaining aspects were ignored or irrelevant. We accounted for 91% of the variance in size judgments using  $L/H$  and  $N^5$ , but the same regression performed with  $L/H$  and  $H/D$  accounted for 85%. The difference between height and spread judgments was not that  $H/D$  was irrelevant for spread judgments, but that  $L/H$  along with the number of branches became especially relevant. ( $L/H$  only accounted for 17% and 5% of the variance in  $H/D$  and  $N^5$ , respectively, in simple regressions.) Judgments of lateral spread placed a heavier emphasis on architectural variations.

Biological forms are complex in exhibiting properties that are inherently integrated and thus inseparable in displays although distinguishable by observers of those displays. The methodological moral is that isolating perceptible properties in displays may often be inappropriate.

*Resolution, memory, and the continuous field.* The complexity of tree forms makes the resolution of form changes difficult. Detecting changes in form would place a heavy load on memory when the images are presented one at a time. In natural environs, these forms populate a structured surround so that scaling information provided by a given tree can be conferred on the background structure and subsequently tuned with additional information. The advantage is that the continuous background serves effectively in lieu of (or at least in aid of) memory. Removal of the structured background may prevent perceivers from making effective use of such complex biological forms.

In Experiment 1, important factors present in natural viewing conditions clearly were missing. Both systematic and random errors were substantially greater for simulated than for real trees. In particular, observers failed to discriminate scaling variations generated by architectural differences. From this, we inferred that the presence of a ground texture gradient might be important in providing a single environmental field on which scaling might be conferred and through which the scaling might be tuned. When a ground texture gradient was used in Experiment 3, the accuracy of the estimates improved, including successful discrimination of architectural scaling variations. Furthermore, the pattern of errors over successive trials indicated that observers fine-tuned and improved their

estimates over the first 15 or so trials, during which systematic errors dropped by nearly 50%. This trend had been absent without the ground texture gradient.

The potential difficulty in including more structure was the possible introduction of confounds. Specifically, with the inclusion of ground texture and a horizon, observers might have used the horizon ratio to achieve the observed improvements in estimates. However, the use of the horizon ratio was not supported by results from judgments of nonbiological objects. In conditions where the horizon ratio was available but information from biological forms was not, judgments of poles and cylinders were highly variable.

The ineffectiveness of the horizon ratio also has been demonstrated by varying the eye height used to generate simulations otherwise like those used in Experiment 3. Bingham (in press-b) used an eye height of 4 m as opposed to 1.7 m. Use of the horizon ratio to judge height requires the use of an assumed eye height value, presumably that of the standing observer. Using the horizon ratio to judge tree height in a simulation projected to more than double the eye height should have cut judgment slopes by at least 50%. To the contrary, the slopes of judgments increased slightly. Clearly, the trees, not the ground texture pattern, were the ultimate source of size information, although the presence of the ground texture did enable observers to use that information more effectively.

#### *Compression in Judgments as a Product of Viewing Conditions*

Mean height judgments in Experiment 3 continued to exhibit a ceiling at about 60 ft (18.29 m). Although we do not fully understand the source of this ceiling, the evidence from judgments of real trees indicates that the pictorial nature of the simulations was responsible. Mean estimates of the tallest trees dropped from near 80 ft (24.38 m) to about 60 ft (18.29 m) when binocular and wide angle vision were eliminated (through-the-tube viewing). Optical flow containing motion parallax was also kept to a minimum by requiring observers to stand still and to provide their estimates within seconds. Maximum judged heights dropped only another 4 or 5 feet when estimates were made from photographs (although the  $r^2$  continued to drop substantially). Whether the lack of wide-angle vision or the lack of the transformations associated with binocular vision and motion parallax were responsible is not clear from the current results. Nevertheless, judgments of simulations were comparable to judgments of real trees obtained under the most similar viewing conditions. Perhaps adding stereopsis or optical flow with motion parallax to the simulations would raise the ceiling. On the other hand, an extension of the ground texture into surrounding near space also might make the difference.

#### *Judgment Accuracy Versus Task and Model Adequacy*

In addition to being compressed, our judgments were somewhat noisy. We might attribute this partially to the oddity of judging sizes in extrinsic units, namely, feet (Bingham,

1993). Whereas the scales entailed by the heights of trees are likely to be relevant to some human activities, we did not invoke any specifically relevant activity and associated intrinsic units in asking our participants to estimate tree heights. Any intrinsic scales are unlikely to be isomorphic to the British scale of length used by our observers. Intrinsic scaling is never homogeneous (Luce, Krantz, Suppes, & Tversky, 1990; Marley, 1992). A functionally constrained intrinsic scale will exhibit maximum as well as minimum values. For instance, if the concern was with the prospect of falling while climbing a tree, then heights over 20–30 ft would be functionally equivalent because any such fall would kill the climber. Thus, we need not have expected observers to be equally accurate or reliable in judging sizes at all scales. The increases in systematic (as well as random) error at increasing heights certainly might have been expected. More to the point, observers were not expected to use the information in any way, so there was no reason to have expected anyone to be particularly skilled at this task. Accordingly, we made no attempt to select skilled observers. In view of this, our observers seem to have performed rather well.

The judgments of real trees provided a baseline for what we might have expected from judgments of simulations. We found that simulation estimates were more error prone than real tree estimates. On the other hand, we generated simulated tree images on the basis of a rather primitive or nascent understanding of tree morphology. According to the principle of similitude, the forms of biological objects change or distort to preserve function in the face of changes in scale. Thus, understanding the physical and functional constraints on biological forms is the key to understanding how specific forms map to specific scales. At present, we have only a portion of the relevant scaling laws at our command. For instance, naive observers confirmed our observation that the simulations appeared less convincing at the low and high ends of the height range. With improvement in our models of physical constraints on form, we might improve our simulations and, by inference, expect to reduce the errors in estimates. When coupled with improved apprehension of those forms through motion parallax or binocular vision, estimates might become very accurate indeed. The bottom line is that we appear to have discovered a new solution to an age-old problem in perceptual psychology.

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## Appendix A

### Determining the Forms of Trees

Hallé, Oldeman, and Tomlinson (1978) described 23 basic architectural models that they hypothesized to capture the diversity of tree shapes generated by specific branching patterns. (See also Tomlinson, 1983.) Despite architectural diversity, all tree forms conform to two scaling relations. The first is based on the essential light-gathering mission of trees; the second is based on mechanical requirements that must be fulfilled by the structure supporting the arrayed light-gathering surfaces.

The primary objective of a tree is to present photosynthetic leaf surfaces to sunlight. Thus, trees grow so as to cover the upper exterior surface of their branching volume with leaves. The leaves are of fairly constant size so that the number of leaves required is directly proportional to the size of the total surface area to be covered (Fisher & Honda, 1979a, 1979b; Honda & Fisher, 1978; Tomlinson, 1983). The total surface area, in turn, is proportional to the square of the tree height (Turrell, 1961). The leaves are attached to terminal branch segments, so the number of branches should be proportional to the square of tree height.

Branch segments are produced in generations by a regular bifurcation of branches that is iterated annually (Fisher & Honda, 1979a, 1979b; Wilson, 1989). Simple iteration of the branching pattern would result in a geometric increase in the number of branches (Borchert & Slade, 1981). However, the growth in branch number is constrained to follow the increase in exterior surface by a hydraulic process that transports water and nutrients to branches within a tree (Borchert & Honda, 1984; Honda, Tomlinson, & Fisher, 1981; Tomlinson, 1983; Zimmermann, 1978a, 1978b.) Branches are pruned when nutrients become unavailable. The availability of nutrient liquids is determined by constraints on root growth and distribution, by angles at branch points, and by transpiration at the leaf surface that creates a siphonlike driving force on fluid flow. Accordingly, the total number of branches is proportional to the total surface area surrounding the branch-filled volume, and thus, the number of branches on a tree is directly proportional to the square of the tree height.

Empirical measure of the scaling between leaf number and tree height has resulted in an exponent that is fractionally greater than 2 (Turrell, 1961). The reason is that trees do not cover their surface area by means of a perfectly efficient monolayer of contiguous, nonoverlapping leaves. Rather, the surface is covered with over-

lapping leaves that form a layer of some depth. The scaling exponent is greater than 2 just to the extent that the leaves tend on average to overlap. Nevertheless,  $N = bH^2$  (where  $N$  is the number of branches and  $H$  is tree height) provides a good approximation to the scaling law determining the increase in branches with increasing tree size (Borchert & Honda, 1984). The value of the coefficient,  $b$ , depends on leaf size or, more precisely, on the size of terminal leaf rosettes. On the basis of observations of many local species, we determined the value of  $a$  by assuming a leaf rosette area of .5 m<sup>2</sup>.

The second scaling law derives from mechanical constraints on self-supporting structures. In competing among themselves for the available sunlight, trees grow to substantial heights. The structure that holds the leaf layer up to the sunlight must be self-supporting and robust in the face of perturbation by wind, rain, snow, and climbing animals. Structural engineering analysis verified by empirical measures has shown that as trees grow in scale, their trunk and limbs exhibit elastic similarity (McMahon, 1975; McMahon & Kronauer, 1976; see also Niklas, 1992; Wilson & Archer, 1979). Elastic similarity preserves the angle formed between a horizontal and a line drawn from the base to the tip of the branch bent under its own weight. The inertia (that is, weight and lever arm) of a branch increases as it grows in length. The stiffness of the branch or its ability to support its inertia depends on its thickness or diameter. Given the constant structural properties of wood, if branch diameter increases in proportion to the 1.5 power of the length, then the increases in stiffness offset increases in inertia and the structural integrity of the branch is maintained. The analysis of the upright trunk in central trunk trees is the same but the focus is on neutral stability of the upright trunk in response to perturbations and, thus, its resistance to buckling.

Elastic similarity predicts that trunk and limb diameter scale to the 1.5 power of the height ( $H$ ) of the trunk or length of the limb respectively, that is, for trunk diameter ( $D$ ):  $D = aH^{1.5}$ . The value of the scaling coefficient,  $a$ , depends partially on the elastic properties of woods. However, the value also varies depending on how closely trees approach the limit at which they buckle (McMahon & Kronauer, 1976). In forest stands where competition is strong, trees approach the limit more closely and the coefficient exhibits smaller values. We used a somewhat larger value that has been demonstrated as appropriate for free-standing trees.

This power law relation grows without bound. McMahon and Kronauer (1976) only tested this relation with trees of heights up to about 14 m. The problem is that trees grow to maximum heights that are characteristic for given climate zones, that is, regions with characteristic patterns of rainfall and temperature (Kira, 1978). The implication is that there are yet other scaling laws contributing to the forms of growing trees. Kira (1978) developed a hyperbolic function to model the relation between trunk diameter and tree height based on measurements of trees in different climate zones. The function was as follows:

$$D = \frac{MH}{a(M - H)}, \quad (\text{A1})$$

where  $D$  is trunk diameter at the base,  $H$  is tree height, and  $M$  is the maximum height for a given climate zone. The significance of the hyperbolic relation (as opposed to a power law) is that the function asymptotes on a maximum value. As shown in Figure A1, the McMahon and Kira relations remain quite close until trees begin to approach maximum heights. The difference is that the empirically derived Kira relation captures additional scaling constraints that have, as yet, to be theoretically determined, constraints that only become apparent near maximum heights.

Equation A1 determines a relation between the actual height of a tree and the ratio of tree height ( $H$ ) to diameter ( $D$ ). The relation is derived by dividing both sides of Equation A1 by  $H$ , which yields:

$$H = M - k \left[ \frac{H}{D} \right]. \quad (\text{A2})$$

Given the symmetry of tree trunks about their long axis, the  $H/D$  ratio is preserved in tree images projected to a point of observation

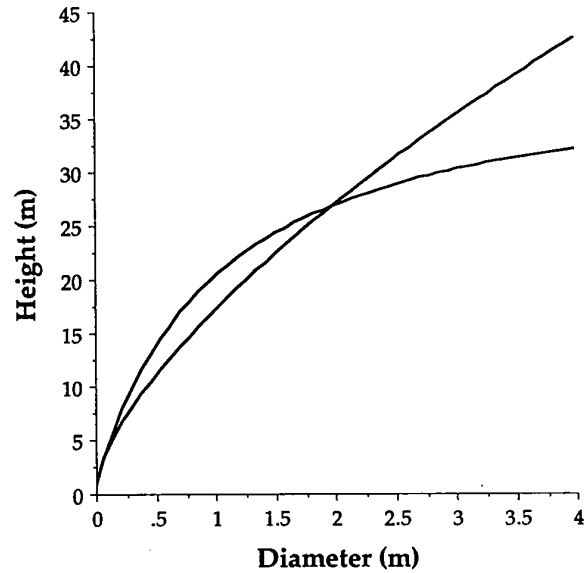


Figure A1. Comparison of the power law (McMahon) and hyperbolic (Kira) functions scaling tree diameter to height. The power law relation predicts unbounded increases in height.

that is sufficiently distant. The geometry of tree viewing is described in Appendix B.

## Appendix B

### The Geometry of Tree Viewing

This appendix shows that optical information exists specifying  $H/D$  for sufficient viewing distances,  $d$ , but that the information begins to underestimate  $H/D$  as viewing distances become small, that is, as the viewing distances approach the viewing height.

First, consider the geometry of viewing the tree diameter,  $D$ , as seen in Figure A2a. The point of observation,  $o$ , is at a distance,  $d$ , from the diameter that is perpendicular to line  $oc$  and through point  $c$  in the center of the tree.  $or$  is tangent to the tree from the point of observation,  $o$ . This ultimately determines the perceived diameter of the tree,  $D' = 2r'$ , which, in turn, corresponds to visual angle,  $2\alpha$ . As can be seen from Figure A2a,  $r' < r$  (and therefore,  $D' < D$ ). As  $d$  increases,  $r'$  approaches  $r$ , reaching  $r$  at limit when  $d$  reaches infinity.

An expression can be developed showing the margin of error, or the proportion between  $r'$  and  $r$ , as a function of  $r$  and viewing distance,  $d$ . Given  $r = d \sin \alpha$ ,  $e = d \cos \alpha$ , and  $r' = e \sin \alpha$ , the following can be obtained:

$$r' = d \cos(\alpha) \sin(\alpha)$$

$$\frac{r'}{r} = \frac{d \cos(\alpha) \sin(\alpha)}{d \sin \alpha} = \cos \alpha = (1 - \sin^2 \alpha)^{0.5} = \left( 1 - \left[ \frac{r}{d} \right]^2 \right)^{0.5}$$

Inverting this expression, a function is obtained into which a desired margin of error may be put to obtain the required ratio between tree

radius and viewing distance as follows:

$$\frac{r}{d} = \left( 1 - \left[ \frac{r'}{r} \right]^2 \right)^{0.5}$$

So, for the perceived  $r'$  to be within 90% of the actual  $r$ , the viewing distance,  $d$ , must be at least  $2.3r$ . Likewise, for 99%,  $d = 7r$ . These are not very stringent requirements. A viewing distance of 15 ft (4.57 m) yields 99% accuracy for trees of trunk diameter of 4 ft (1.22 m) or less. Assuming viewing distances of at least 15 ft, we use the approximation shown in Figure A2b, for which  $r/d = \tan \alpha$ , and so  $r = d \tan \alpha$  and  $D = 2r = 2d \tan \alpha$ .

Turning next to the geometry of viewing tree height,  $H$ , the situation appears in Figure A2c. An observer of eye height,  $h$ , at point of observation,  $o$ , is at a perpendicular distance,  $d$ , from the tree trunk. The viewing angle from the horizontal to the bottom of the tree is  $\beta_1$  and the viewing angle to the top of the tree is  $\beta_2$ . Angles above the horizontal are negative. From this we obtain  $d = T_1 \cos \beta_1$ ,  $d = T_2 \cos \beta_2$ , and  $H = [T_1 \sin \beta_1] - [T_2 \sin \beta_2]$ , where recall for the latter that  $\sin(-x) = -\sin(x)$ . Setting  $H$  over  $d$  we obtain  $H/d = \tan \beta_1 - \tan \beta_2$ , so that  $H = d [\tan \beta_1 - \tan \beta_2]$ . Note that  $\tan(-x) = -\tan(x)$ , also.

To bring the two expressions for  $D$  and  $H$  together, we first note that the distance from  $o$  to the diameter at the base of the tree is  $T_1 = [d^2 + h^2]^{0.5}$  and that this must replace  $d$  in Figure A2b and in the

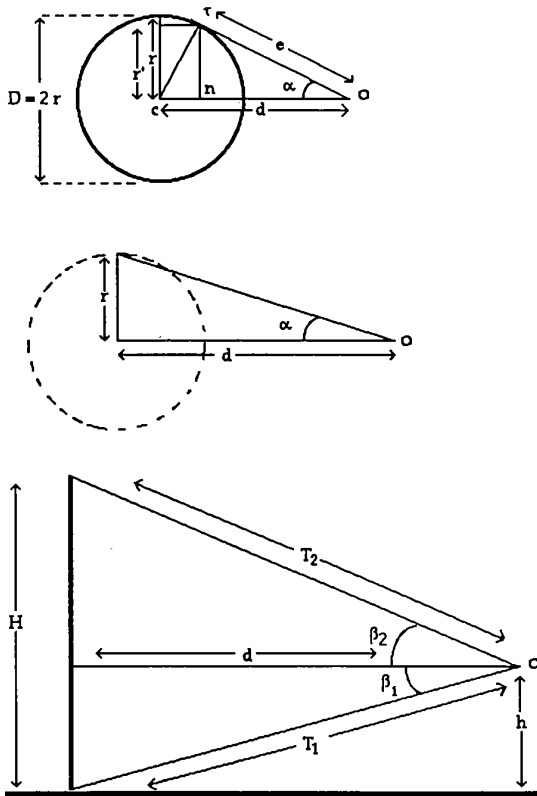


Figure A2. The geometry of viewing trees. Top: The geometry of viewing trunk diameter. See the text for explanation. Middle: The approximation used for viewing at sufficient distance. Bottom: The geometry of viewing trunk height.  $H$  is tree height,  $h$  is eye height,  $o$  is the point of observation,  $d$  is the viewing distance. See the text for further explanation.

expression for  $D$  so that

$$D = 2\sqrt{d^2 + h^2} \tan \alpha.$$

Using this and the expression for  $H$ , we obtain

$$\frac{H}{D} = \frac{d[\tan \beta_1 - \tan \beta_2]}{2\sqrt{d^2 + h^2} \tan \alpha} \tag{B1}$$

The optical information about the  $H/D$  ratio is as follows:

$$\frac{H}{D} \cong \frac{[\tan \beta_1 - \tan \beta_2]}{2 \tan \alpha} \tag{B2}$$

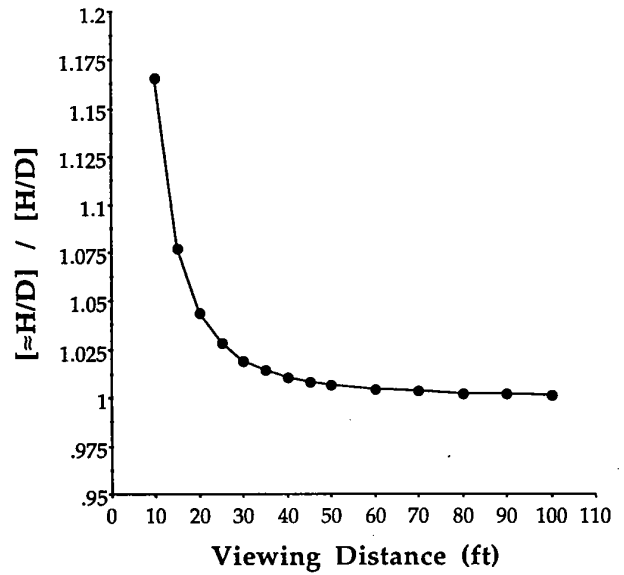


Figure A3. The ratio of optical  $H/D$  to actual  $H/D$  with increasing viewing distance.

The condition for the strict equivalence of Equations B1 and B2 is

$$1 \cong \frac{d}{\sqrt{d^2 + h^2}} \tag{B3}$$

This is satisfied when  $h = 0$ , that is, when the point of observation is at ground level. However, in general, Equation B2 approximates Equation B1 where the error of the approximation is determined by the magnitude of  $d$  in relation to  $h$ . Thus, for  $h = 6$  ft (1.83 m),  $H/D$  is accurately specified at viewing distances sufficiently larger than 6 ft. The degree of difference between  $H/D$  as determined by Equation B2 as opposed to Equation B1 for  $h = 6$  ft is shown in Figure A3 where the ratio of  $H/D$  computed using Equation B2 to  $H/D$  computed using Equation B1 is plotted as a function of viewing distance.

Finally, we note that analytically accurate estimates of tree height could be obtained using Equation B2 by setting  $h = 0$  at eye height and estimating tree height only for that portion above eye height and then adding the eye height value to the resulting tree height estimate, assuming that eye height is known.

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