Perceiving the Size of Trees Via Their Form

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Abstract

Physical constraints on growth produce continuous variations in the shape of biological objects that correspond to their sizes. We investigated whether two such properties of tree form can be visually discriminated and used to evaluate the height of trees. Observers judged simulated tree silhouettes of constant image size. Comparison was made to judgments of real trees in natural viewing conditions. Tree form was shown to confer an absolute metric on ground texture gradients. Eyeheight information was also shown to be ineffective as an alternative source of absolute scale.

Introduction

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, by itself, 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 (Gogel, 1977; Holway & Boring, 1941; Kilpatrick & Ittelson, 1953). 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; Gogel, 1977; Gibson, 1950; Hartmen & Harker, 1957;).

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 man made objects, like playing cards, matchbooks, and watches, because the relevant forms are distinct and the sizes are well restricted. Application to biological objects is more 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. 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.

A second consideration is associated with a requirement that sizes be restricted and highly stable. Such regularity and predictability is produced by constraints impinging on the formation of the objects in question. The sizes and forms of biological objects are constrained by physical and biological laws. The study of such laws comprises the subject matter of functional morphology and allometry[1] (Calder, 1984; Hildebrand, Bramble, Liem & Wake, 1985; McMahon, 1984; McMahon & Bonner, 1983; Peters, 1983; Thompson, 1961). D'Arcy Thompson (1961) has described organic form as a "diagram of forces" and, following observations of Galileo,

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[1] 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).

has noted that organic forms alter in the face of scale changes to preserve the integrity of structure and function. The forms must change because various linear or geometric dimensions in an object 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 while the weight to be supported is proportional to the cube of its length. As the bone increases in size, the diameter must increase faster than the length for the strength be adequate 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. This is true in particular of the forms assumed by vegetation.

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 couple of feet to a couple of hundred feet. Do specific continuous variations in tree form accompany such variations in size? If so, can observers distinguish such continuous variations in form and use such information to evaluate size?

For a number of reasons, perceiving the size of trees 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 span the greater part of 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. The scaling laws that determine changes in form accompanying changes in size with growth have been described (Borchert & Honda, 1984; Fisher & Honda, 1979a, b; Honda, Tomlinson & Fisher, 1981; McMahon & Bonner, 1983; McMahon & Kronauer, 1976; Turrell, 1961). 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). 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 employ 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). The diameter of a branch or tree trunk scales with the remaining length along the branch or trunk to its tip as follows:

$$\text{Diameter} = (\text{Height})^{1.5}.$$

This is consistent with an empirically derived relation which also predicts maximum heights for given climate zones (Kira, 1980). 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.) Because the H/D ratio is well preserved in tree images, the relation determines optical information for tree height. Using the Kira relation for temperate zone trees:

$$\text{Actual Height}=131.23 - 3.28(H/D).$$

Second, the number of terminal branches in a tree scales with the size of the tree (Borchert & Honda, 1984; Turrell, 1961). To an approximation, a tree covers the surface of its branching volume with leaves of constant size to collect light. Branches are required in constant proportion to the leaves. An exponential branching process is constrained by the hydrodynamics of the neutrient distribution producing conformity to a surface law (Borchert & Honda, 1984; Honda, Tomlinson & Fisher, 1981). This has been confirmed (Kira, 1980; Turrell, 1961) and predicts:

$$\text{Number of branches}=a(\text{Height})^{2}.$$

Thus, the number of branches, a property well preserved in images, also provides information about tree height.

Judging isolated silhouettes and real trees

Can observers use forms generated by such scaling relations to judge tree size? Using the two scaling relations, we produced tree silhouettes of constant image height in 7 different architectures (Halle, Oldeman & Tomlinson, 1978; Honda, 1971; Tomlinson, 1983)[2]. 24 observers first judged the height of 16 real trees observed on the IU campus at distances preserving constant image heights equivalent to our simulated images. Actual heights ranged from 10 ft-90 ft. O's next judged heights of simulated trees viewed as silhouettes (parallel projection) with no background structure.

O's judging real trees were instructed to judge height in feet by glancing rapidly at the specified tree and writing a quick, "off the cuff" assessment of the height. Each judgment was made in a period of about 2-3 seconds. Before making these judgments, participants were shown a short (26 ft) and a tall (64 ft) lighting pole and were told the heights. A regression showing mean judgments (with standard error bars) against actual heights appears in Figure 1. The rather surprising accuracy given the rapidity of judgments is reflected by a mean slope of .9 and intercept near 0. r^2 for the individual judgments was .81.

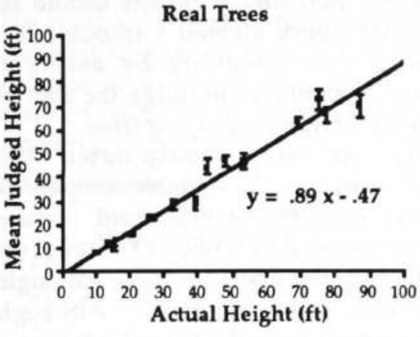

Figure 1.

O's also judged height in feet for the simulated tree silhouettes. O's were given packets in which each page contained a single tree image. 56 trees varying in height and architecture were arranged in 2 random orders. O's flipped through the packets writing their judgments in order and then were allowed to go back to adjust their judgments after having studied the whole set of tree images. The mean height judgments with standard error bars appear in Figure 2 compared to actual modeled heights for each of the 7 architectures.

On average, judgments were monotonically increasing with increasing actual height. Rank orderings of mean height judgments were computed simultaneously across all 56 trees as were orderings according to actual modeled height, number of branches, and the D/H ratio. The ordinal relations for trees across all 7 architectures were accurately reproduced in judgments with the exception of one of the architectures. O's were also asked to rate the naturalness of the tree images. O's rated the architecture with poor ordinal results as the least natural or realistic. Overall, however, the images were rated as realistic.

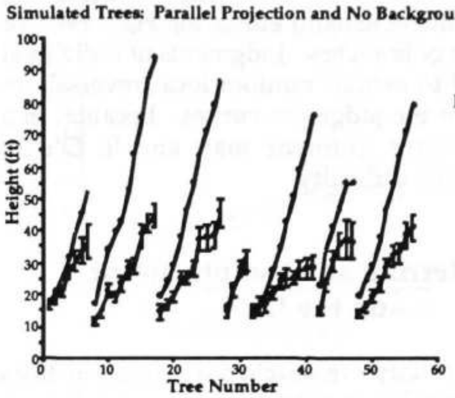

Figure 2.

The scaling relation between actual height and the H/D ratio predicted by the Kira relation was linear. The relation for modeled and judged heights was linear in both cases. When H/D and number of branches were regressed simultaneously on modeled heights, both H/D and number of branches were significant, $p<.001$, with almost equal beta weights of opposite sign. (Overall $r^2=.902$.) In the same regression performed on height judgments, only H/D was significant with a beta weight that dwarfed that for number of branches. (Overall $r^2=.914$.) Thus, judgments seemed to have depended primarily on the H/D ratio. Of course, because the H/D ratio and the number of branches covary to a large extent, the number of branches cannot be irrelevant to either height or size judgments. In pilot studies using simulations that only varied the H/D ratio, not branch number, some O's refused to perform the task because the information was contradictory.

The obvious problem with the simulation results was that, while the judgments were well ordered, the slopes were shallow. The overall slope for actual heights regressed on judged

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[2] Rolf Borchert provided us with the program described in Borchert & Honda (1984) which simulated branching as determined by the hydrodynamics. M. Stassen, E. Gutjahr, and I incorporated routines to compute tree diameters and to draw trees, ground texture, and cylinders in perspective.

heights was .37. Mean judgments did not exceed 45 ft while modeled heights reached 90 ft. Why should this have been so? One possibility is that the simulation viewing conditions may have been so reduced as to distort the forms and suppress judgments. The tree images were all produced using parallel projection for all sizes and distances. As a result, the images were all extremely flat and, for nearer trees, distorted. Also, if we wished to compare simulation results to the judgments of real trees in more natural viewing conditions, then the lack of a ground texture gradient may have been significant. O's may have had some difficulty in resolving successive increments in either the H/D ratio or the number of branches. Judgments of individual O's tended to exhibit random local reversals or flattening of the judgment curves. Location in a ground texture gradient may enable O's to overcome this difficulty.

Conferring an absolute metric on the field

For the next study, we sought to make simulations more comparable to natural viewing conditions. We used polar projection and placed the trees in the context of a ground texture gradient. A sample image appears in Figure 3.

Use of a ground texture gradient introduced another interesting question. Like motion parallax, texture gradients provide information about relative distances, but not about absolute distances. Might the trees confer an absolute scale on the ordinal (or interval) field set up by the gradient? We investigated whether the trees can be used, in the context of a ground texture gradient, to scale the absolute size of other objects with Platonic forms. We placed 6 cylinders at various locations within the gradient. Cylinder size was varied to preserve image size.

This manipulation also allowed us to control for another hypothesized effect of ground texture information. Use of information associated with eyeheight has been hypothesized to confer an absolute metric on both parallax and texture gradients (Lee, 1980; Mark, 1987; Warren & Wang, 1987). On a flat ground plane, the image of the horizon has been shown to cut across the images of all objects in the field of view at a height corresponding to the height of the point of observation. If this is the source of any observed improvements in the accuracy of judgments made of simulations with ground texture gradients, then similar results should be obtainable for cylinders viewed without trees. We investigated this possiblity by asking a separate group of observers to judge the size of cylinders without viewing or judging trees.

Finally, we also manipulated the viewing of real trees to make it better comparable to the original simulations. Ground texture information was reduced by having O's view trees through a tube with an aperture of visual angle slightly larger than that of the trees. Although the ground extending from the O to the tree was occluded, some ground texture remained visable immediately around a given tree. The results for 10 O's appear in Figure 4. Restricted viewing dropped the slope from .9 to .8. A multiple regression performed on the combined data from restricted and unrestricted viewing with vectors for actual height, viewing condition, and the interaction was significant, $p<.001$, $F(3,372)=504.6$, $r^2=.80$. Actual height was significant, $p<.001$, partial $F=1186.4$. Viewing was not significant, but the interaction was significant, $p<.05$, partial $F=4.06$. Thus, restricted viewing resulted in a change in slope, but no change in intercept. Mean judgments did not exceed 60 ft.

Using the same procedure as before, 17 O's judged simulated trees in the context of a ground texture gradient. Only 6 architectures were used excluding that poorly rated in the previous study.

The mean height judgments with standard error bars appear in Figure 5 compared to actual modeled heights for each of the 6 architectures. Overall mean slope was .48, greater than for isolated silhouettes, but still less that for reduced viewing of real trees. However, as shown in Figure 5, the result of a linear fit is misleading. Mean judgments were linear and close to actual values for heights up to about 40-50 ft at which point judgment curves appear to hit a ceiling. The source of this effect remains to be determined. The good fit between mean judgments and actual modeled heights for trees below 40 ft reveals an absence of a 'contraction effect'. The ceiling reached after 40 ft may reflect difficulty in resolving subsequent increases in diameter or branch number.

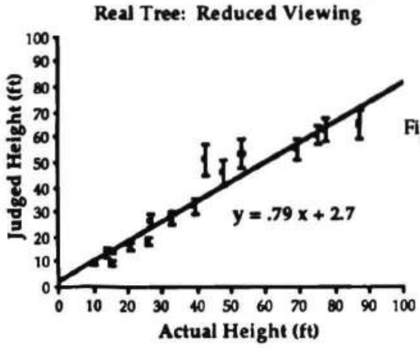

Figure 4.

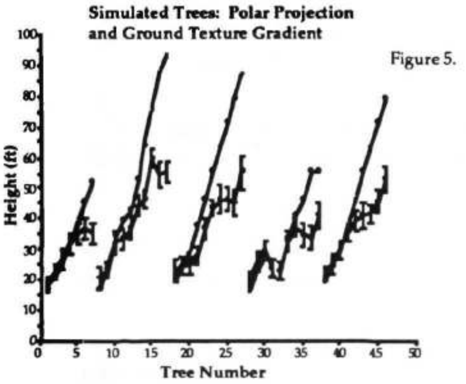

Figure 5.

When asked to judge the height of the cylinders, O's who had not seen the trees produced judgments that were ordinally correct but highly variable in absolute value as shown in Figure 6. Mean slope was .88. Mean judgments were high. Random variability was large. In contrast, O's who had first seen the trees appearing in the context of the cylinders produced judgments that were systematic and much more accurate as shown in Figure 7. Mean slope was .57, close to the slope for the tree judgments. Random variability was low in comparison.

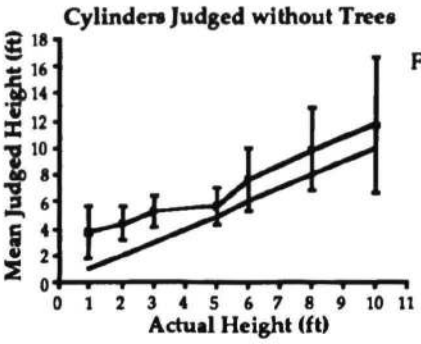

Figure 6.

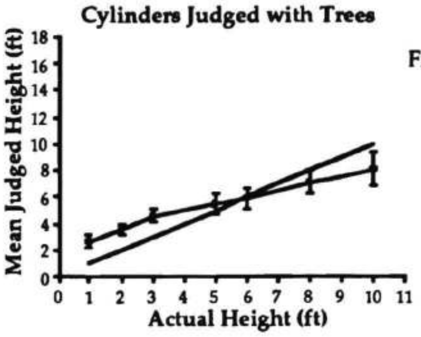

Figure 7.

Conclusions

We have a new solution to the old problem of size perception. The ability to discriminate subtle variations of this complex bioligical form was sufficient to enable people to use the information to judge scale. The information conferred an absolute metric on a ground texture gradient. In contrast, eyeheight information was ineffective.

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