Allometry and Space Perception: Compression of Optical Ground Texture Yields Decreasing Ability to Resolve Differences in Spatial Scale

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Robert E. Shaw and colleagues showed that allometric variations in biological forms provide visual information about the spatial and temporal scale of biological objects (Mark, Todd, & Shaw, 1981; Pittenger & Shaw, 1975a, 1975b; Pittenger, Shaw, & Mark, 1979; Pittenger & Todd, 1983; Shaw, Mark, Jenkins, & Mingolla, 1982; Shaw & Pittenger, 1977, 1978). In these studies, form changes due to growth of the human head and body were investigated. Subsequently, Bingham (1993a, 1993b) extended these ideas to plant growth and tree perception. Using extant models of tree growth and morphology, 2 allometric relations were simulated. One determined the thickness of tree branches and the other determined their numerocity. The investigations showed that the resulting tree forms could be used by observers to judge tree size. Trees appearing in the context of a ground texture gradient conferred metric scaling on the field that enabled observers to judge the size of other nonbiological objects appearing elsewhere in the context of the ground texture. Results were replicated using actual trees outdoors, pictures of actual trees, and computer generated simulations. In all cases, judgments were accurate at near distances and increasingly underestimated tree size at greater distances. The authors hypothesize that it becomes increasingly difficult to resolve differences in the size and distance of trees as the density of ground texture elements and of branches becomes high. The results of a single study support this surmise. The authors suggest that the accelerating compression of the previous judgment curves was due largely to this effect.

The scaling problem in visual space perception derives from the fact that spatial metrics are absent in optical patterns. Spatial extents in the optic array are angular, not

linear. This is why image size by itself cannot provide information about the corresponding object size. A proposed solution to this problem was formulated by Kepler (following his analysis of image formation by lenses; as cited in Lombardo, 1987). The solution was to impose a linear spatial metric on the optics using the viewing geometry and the positions and orientations of the eyes as they fixate on a common locus in the surrounds. This is binocular vergence, and the resulting metric unit is the distance between the two eyes. This is the unit traditionally implicit in size–distance invariance theory, which uses the distance metric, image size, and viewing geometry to derive object size and, potentially, a metric scaling for the spatial surrounds (Hochberg, 1961; Palmer, 1999). A general scaling could be obtained, for instance, from determination of the size of ground surface texture elements.

Most solutions to the scaling problem in space perception are similar in imposing a metric on the optics using viewing geometry and a dimension of the observer's body or its movement. For instance, the horizon ratio entails the eye height of the observer (Schiff, 1980). Similarly, absolute scale could be obtained from motion parallax using the amplitude (or speed) of observer movement.

The notable alternative to these solutions is familiar size theory, which holds that the size of a recognizable object is simply known (Hochberg, 1961; Palmer, 1999; Schiff, 1980). This solution entails the assumption that given types of objects are invariably of a given size. In turn, this entails constraints that yield the invariance (Bingham, 1993b). Familiar objects are often human artifacts whose size is functionally constrained by human uses and thus by human scale. Implicitly, physical and functional constraints on human scale thus constrain the scale of such familiar objects. By direct extension, other nonhuman biological objects might be constrained in size in a similar way. The problem is that biological objects are subject to growth and thus large changes in size. Thus, mere recognition of a familiar animal or plant would determine its size only within a potentially large range allowed by normal growth from the infant to the adult form or from the seedling to the towering oak.

In the 1970s and early 1980s, Robert E. Shaw and his colleagues attacked this problem and showed that familiar size as applied to biological objects is not limited to specifying only the range of possible sizes entailed by growth. Instead, the particular scale within the range allowed by growth can be perceived. The solution was allometric and was inspired by the work of D'Arcy Thompson (1917/1961) described in his book *On Growth and Form*. Properties of the forms of objects are preserved in optical images and provide information allowing familiar objects to be recognized. Thus, form is the basis of the familiar size solution to the scaling problem. *Allometry* is the study of the way biological forms necessarily change or transform to preserve function in the face of physical changes that occur with changes in size (Niklas, 1994). Because form changes covary with scale changes, forms can be used as information about scale.

Galileo (1638/1914) provided an early example of allometry. He observed that although the weight of a bone is proportional to its volume and thus to the

cube of its linear dimension, the strength of the bone or its ability to support the weight is proportional to its cross sectional area and thus to the square of its linear dimension. As the size of a bone is increased, its weight increases much more rapidly than its strength if its shape is unaltered, that is, if the relation between volume and cross-sectional area stays the same. The result is that the bone would fail. To preserve its function, the strength of the bone must be increased in proportion to its weight, and this, in turn, means that the shape must be transformed as the size is increased to keep the cross-sectional area in proportion to the volume.

Shaw's studies focused more on event perception than on space perception. (Shaw, McIntyre, & Mace, 1974). He was interested in the perception of growth as a slow event, describing it in the same way that any event would be characterized, that is, in terms of a continuous transformation. He and his coinvestigators investigated the ability of observers to detect this transformation and use it to judge the age level of various animals, including humans. They investigated perception of age level either from changes in the entire body (Pittenger & Todd, 1983) or from changes in only the head (Mark, Todd, & Shaw, 1981; Pittenger & Shaw, 1975a, 1975b; Pittenger, Shaw, & Mark, 1979; Pittenger & Todd, 1983; Shaw, Mark, Jenkins, & Mingolla, 1982; Shaw & Pittenger, 1977, 1978). Growth of the head was modeled as a cardioidal strain transformation that was chosen to capture the effects of the forces acting on the head during growth (Shaw et al., 1982). Allometry is essentially the study of dynamic similitude that defines similarity in terms of the underlying dynamics rather than the geometry of an object or the kinematics of an event. The geometry or kinematics transform with changes in size as the dynamical configuration of forces is kept invariant. Shaw et al. found that observers were able to judge age level from head or body shape. However, they did not investigate whether observers could judge body size.

Bingham (1993a, 1993b) investigated whether the allometric form solution to the scaling problem would generalize to the traditional space perception problems of size and distance perception. He also investigated whether the solution would generalize to plants and in particular to trees. The value of testing tree perception, in particular, is that trees span a large range of sizes from 1 m to over 30 m in height. Thus, a large range of sizes and distances could be tested. Furthermore, Bingham investigated whether the perceived tree sizes would confer an absolute scaling on the elements of a ground texture gradient in which the tree appeared so that the size of other nonbiological objects appearing elsewhere on the ground at other distances might be judged. Two different allometric relations were relevant to tree forms. One was an elastic similarity scaling that determined the thickness of tree trunks and branches as a function of the tree size. The other was a surface law that determined the numerocity of terminal branches also as a function of tree size. These relations and the resulting tree forms were found to enable observers to judge both tree sizes and the sizes of other nonbiological objects appearing at other distances along a common ground texture.

Although observers did judge tree sizes reliably and fairly accurately, the judgments tended to increasingly underestimate tree sizes as the trees became increasingly distant. That is, for larger trees viewed at greater distance, the judgments became increasingly compressed relative to the actual range of tree sizes. We now hypothesize that this result was a function of the increasing density of the optical ground texture. The idea is that the density of the optical ground texture made it difficult to resolve differences in distance. Image size was controlled in Bingham (1993a, 1993b) by holding it constant. Thus, larger trees were viewed at larger distance and the branching of the trees was also dense. Thus, there may have been similar difficulty in resolving differences in size.

We now investigate this hypothesis. This test also provides additional evidence that tree form as information about tree size scales the entire field, including all objects appearing in the context of the same ground texture. The paradigm was to present observers with displays consisting of three simulated trees appearing in the context of a simulated ground texture (see Figure 1). The simulations were generated as described in Bingham (1993a, 1993b). Two of the trees appeared on the left and right sides of the display. These trees were always placed correctly within the ground texture gradient given the trees actual (modeled) size and their image size. The third tree was placed in the middle of the display and at one of seven distances along the ground texture. Assuming the scaling established by the two trees to the left and right, three of the distances of the middle tree were too close to the viewer given the actual size and image size of the tree, three of the distances were too far, and one of the distances was correct. Observers were asked to judge whether the middle tree appeared at the correct distance given the sizes and distance of the left and right trees. Observers were also asked to rate their confidence in judging the correctness of the placement. Three different correct locations were tested: near, medium, and far. The expectation was that observers would be better able to judge the near set of locations than the far set of locations.

METHOD

Participants

Sixteen undergraduates at Indiana University participated in the experiment. Eight were men and 8 were women. All had normal or corrected to normal vision. Participants were paid at $5 per hr.

Display Generation

The methods for generating the trees and ground texture are described in detail in Bingham (1993a, 1993b). Two different models governing trunk/branch thickness and numerocity, respectively, were used to "grow" simulated trees of heights from
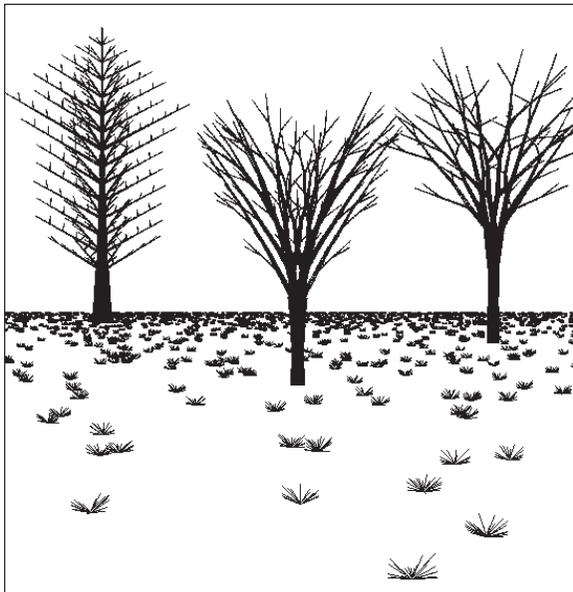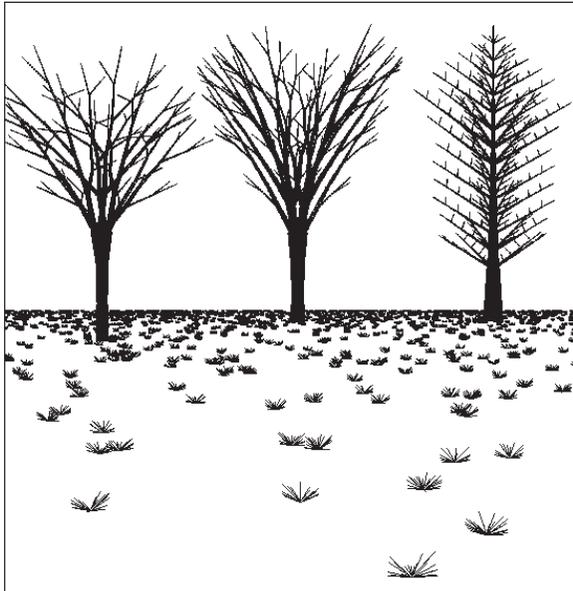
FIGURE 1 Examples of the displays. Trees on the left and right are correctly located along the ground texture gradient given their modeled actual size and image size. The target tree to be judged is in the middle. The target tree is of medium size (top). The target tree is correctly located (bottom). The target tree is located incorrectly along the ground texture gradient. It is in a position that is too near.

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7.72 m to 30.48 m. Three of the seven architectures from Bingham (1993b) were used: V, C, and P. The first two simulate deciduous trees like maples or oaks and the last simulates a pine. Trees appeared on a simulated ground texture that was a flat plane covered by tufts of grass.

Each display consisted of three trees. A target tree appeared in the middle of the display. Three different correct target distances were simulated for each of the three architectures. Because the image sizes were held constant, viewing distances were determined by simulated tree heights: a 7.72 m tree at near distance ($\approx$7.01 m), a 16.76 m tree at medium distance ($\approx$14.63 m), and a 27.43 m tree at far distance ($\approx$23.46 m). Target trees (of the same actual heights and image sizes) were also presented at six different incorrect distances (locations on the ground texture), three too close and three too far. The near distances were 3.02 m, 3.69 m, 4.82 m, 6.98 m (correct), 10.21 m 13.47 m, and 16.70 m. The medium distances were 6.19 m, 7.72 m, 10.0 m, 14.75 m (correct), 21.92 m, 29.05 m, and 36.18 m. The far distances were 9.72 m, 11.95 m, 15.85 m, 23.41 m (correct), 34.87 m, 46.33 m, and 57.79 ft. Two other trees appeared to either side of the target tree. These were of the other two architectures, respectively. Each of these trees were of heights different from any of the target heights, one selected from a range between small and medium and the other from a range between medium and large. Each of the remaining two architectures for each target appeared both to the left and the right and at heights from both ranges. This yielded four "frames" for each target architecture. These frames were randomly assigned to the set of target and test distances for each target architecture. Three architectures times three target distances times seven test distances would yield 63 displays. Displays were printed as high contrast black and white images on 8.5 in. × 11 in. paper. However, the greatest test distance at the far target distance was not included because the trees appeared to sit right on the horizon and the display was simply exceptional.

Procedure

Each participant sat before a table on which a stack of the images was placed. Displays were organized in random orders. The judgment task was described to the participant, who was told that the trees to the left and right were placed correctly and the task was to judge the middle tree relative to the other two and decide whether it appeared at the correct distance along the ground given its size. The participant judged the correctness of each display (yes or no) and then flipped it over and to the side to view the next display. After going through the entire set, the participant went back through and adjusted his or her judgments and also judged on a scale of 1 (*not so wrong*) to 5 (*very wrong*) how wrongly placed each tree was if it was judged incorrect, or if it was judged to be correctly placed, the participant judged his or her confidence of this on a scale of 1 (*not confident*) to 5 (*confident*).

RESULTS AND DISCUSSION

We performed analysis first on the adjusted correctness judgments and second on the wrongness and confidence judgments. The mean proportions of displays judged as correct is shown in Figure 2. (*Note:* To judge as correct here is not necessarily to judge correctly.) The result was that correctly and incorrectly placed trees were distinguished at the near and medium distances but not at the far distance. At the near distance, the location that was just closer than the correct location was judged as correct most often, that is, 85% of the time. The location that was actually correct was judged correct only 58% of the time. Locations that were increasingly too close or too distant were increasingly judged as incorrect. The most distant location was judged as incorrect 71% of the time. At the medium distance, the correct location was judged as correct 75% of the time. Locations closer and farther than this were judged as correct increasingly less often as the misplacement increased. Finally, at the large distance, all locations were judged essentially at chance. The correct location was judged as correct 54% of the time. The most incorrect location was also judged as incorrect 54% of the time.

We performed a mixed design analysis of variance (ANOVA) on these judgments with gender as a between-subjects factor and test distance (7 levels), target distance (3 levels), and architecture (3 levels) as repeated measures factors. Test distance was significant, $F(6, 84) = 4.4, p < .001$. Overall, correct distances were judged as correct more often than incorrect distances. Architecture was signifi-
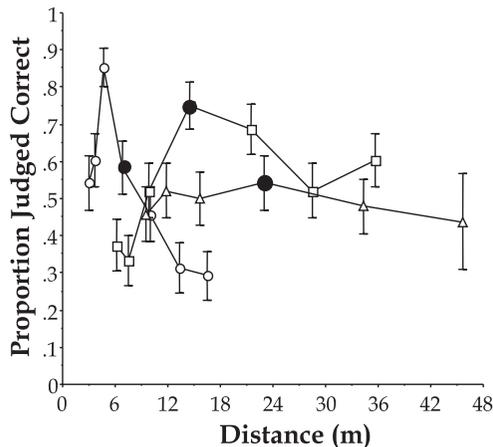

FIGURE 2   Mean proportions of judgments that the target tree is in the correct location plotted as a function of simulated viewing distance. A 0.5 proportion is chance. Means were averaged across the three architectures. The near set of locations is plotted as open circles, the medium set as open squares, and the far set as open triangles. A large back dot in each case marks the correct location in each set. Error bars are standard errors.

cant, $F(2, 28) = 3.8, p < .05$. Architecture P (pine) was judged as correct more often than the other two architectures. The test distance by target distance interaction was significant, $F(12, 168) = 3.5, p < .001$. As shown in Figure 2, correct test distances were distinguished at the near and medium target distances but not at the far target distance. Finally, the test distance by architecture interaction was significant, $F(12, 168) = 2.0, p < .05$. Incorrect near test distances were judged as correct more often for the P architecture than for either the C or V architecture.

The pattern of results was essentially the same once the wrongness and confidence judgments were taken into account. Recall that if a display was judged as incorrect then a wrongness judgment was required between 1 (*less wrong*) and 5 (*most wrong*), and if a display was judged correct then a confidence judgment was required between 1 (*maybe correct*) and 5 (*certainly correct*). We multiplied wrongness judgments by –1, and then, for each of the 20 tree locations, we combined these negative wrongness judgments with the confidence judgments; that is, if the display was judged incorrect then there was a corresponding negative wrongness value, and if the display was judged correct then there was a corresponding positive confidence value. Means were computed for each of the 20 possible tree locations, and these were plotted in Figure 3. The wrongness and confidence judgments simply replicated the proportions of correctness judgments. Using two-tailed t tests, we tested the means at each of the 20 locations for difference from 0. Counting from left to right the 7 means in Figure 3 for each of the three target distances (near,
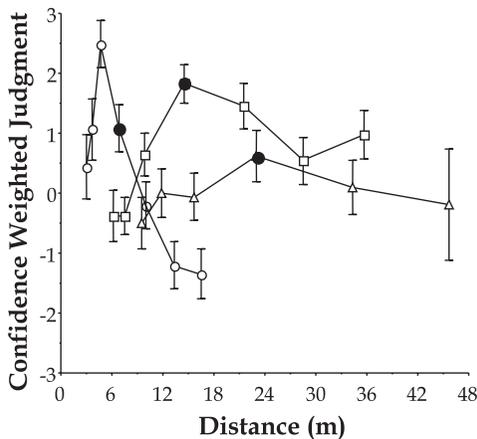

FIGURE 3   Mean judgments are weighted by negative mean wrongness judgments if the location is judged incorrect and by positive confidence judgments if the location is judged correct. A mean of 0 indicates inability to judge correctness of the location on average. Means were averaged across the three architectures. The near set of locations is plotted as open circles, the medium set as open squares, and the far set as open triangles. A large back dot in each case marks the correct location in each set. Error bars are standard errors.
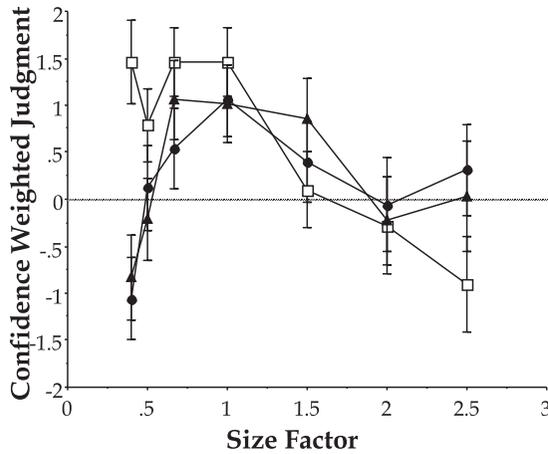
FIGURE 4   Mean judgments are weighted by negative mean wrongness judgments if the location is judged incorrect and by positive confidence judgments if the location is judged correct. A mean of 0 indicates inability to judge correctness of the location on average. Means were averaged across the three viewing distances. The means for architecture P are plotted as open squares, for architecture C as filled circles, and for architecture V as filled triangles. Means are plotted as a function of the size factor, that is, the actual size specified by the location along the texture gradient together with the image size (but not the form of the tree). A size factor of 1 means that the size specified by the form of the tree is the same as that specified by the location along the ground texture gradient together with the image size. Error bars are standard errors.

medium, and far): the 3rd, 6th, and 7th means were different from 0 ($p < .05$) at the near distance; the 1st, 2nd, 4th, and 5th means were different from 0 ($p < .05$) at the medium distance; and only the 1st mean was different from 0 ($p < .05$) at the far distance. When we performed the same mixed design ANOVA on these data as before, the pattern of results was the same as for the correctness judgments. Significant main effects were obtained for test distance, $F(6, 78) = 6.1, p < .001$; and architecture, $F(2, 26) = 4.3, p < .05$. Significant interactions were found for test distance by target distance, $F(12, 156) = 4.1, p < .001$; and test distance by architecture, $F(12, 156) = 3.8, p < .001$. Means for each of the architectures by test distance are shown in Figure 4.

GENERAL DISCUSSION

There were two goals for this study. First, we intended to confirm the results of the previous studies showing both that allometric tree forms provide information about tree size and that this scaling information confers a metric scale on elements in a

ground texture gradient. The latter yields a metric scaling of the entire field. The results of this study confirmed this finding. The two correctly placed trees on the left and right sides of the displays scaled the entire field so as to enable observers to judge whether the target tree placed in the middle of the display was in fact correctly located along the ground plane given both the form (and thus perceptible size) and the image size of the tree.

Second, we tested the hypothesis that trees at increasing distances along the ground plane become more difficult to discriminate in terms of their size and distance. This would be expected simply from Weber scaling of the corresponding ground texture density, tree branching density, and relative increment size of trunk and branch thickness. For instance, Weber ratios for changes in terminal branch numbers over successive generations are near 1 for the smallest trees but below 20% for the largest trees. The results were that indeed distant trees were discriminated only at chance whereas trees at near or medium distances were successfully discriminated as being placed correctly or incorrectly within the field.

Two results obtained in this study were not anticipated. The first is shown in Figure 4. Incorrectly near locations were tolerated for the pine tree architecture and judged as correct. This did not occur with the other two (deciduous) architectures. A comparison of the displays for the small target trees for each of the three architectures is shown in Figure 5 in which the target trees appear in the nearest incorrect location. In Figure 5, it is evident that the thickness of the pine tree trunk appears rather less than that of the other two tree types. This is due directly to the architectural differences in branch geometry. The branching angles are much larger in the pine so the initial branches depart more rapidly from the trunk, making the trunk appear relatively thinner than in the other two architectures in which, because of the shallow branching angles, the initial branches essentially combine with the trunk to increase its effective thickness. The results show clearly that observers are using this information.

The second unexpected result was that the smallest trees in all three architectures were judged to be correctly located at the position just closer than the modeled correct position. As discussed in Bingham (1993b), the tree growth models used in these simulations are imperfect, and, according to visual assessments reported in that article, the failure is greatest for the smallest trees. Improved models of tree growth and morphology would presumably correct these results.

The bottom line in this study is that the allometric forms of biological objects definitely yield information about spatial scale and thus yield an important solution to the scaling problem in space perception. Physical constraints on natural geometry generate structure that remains invariant in optical patterns and enables perceivers to remain grounded in the natural world. Gibson (1973) argued that formless invariants provide detectable information for perceivers. These are the continuous transformations studied by Shaw in the context of growth as a slow event. Shaw pursued Gibson's insight in search of what Runeson (1977/1983) sub-
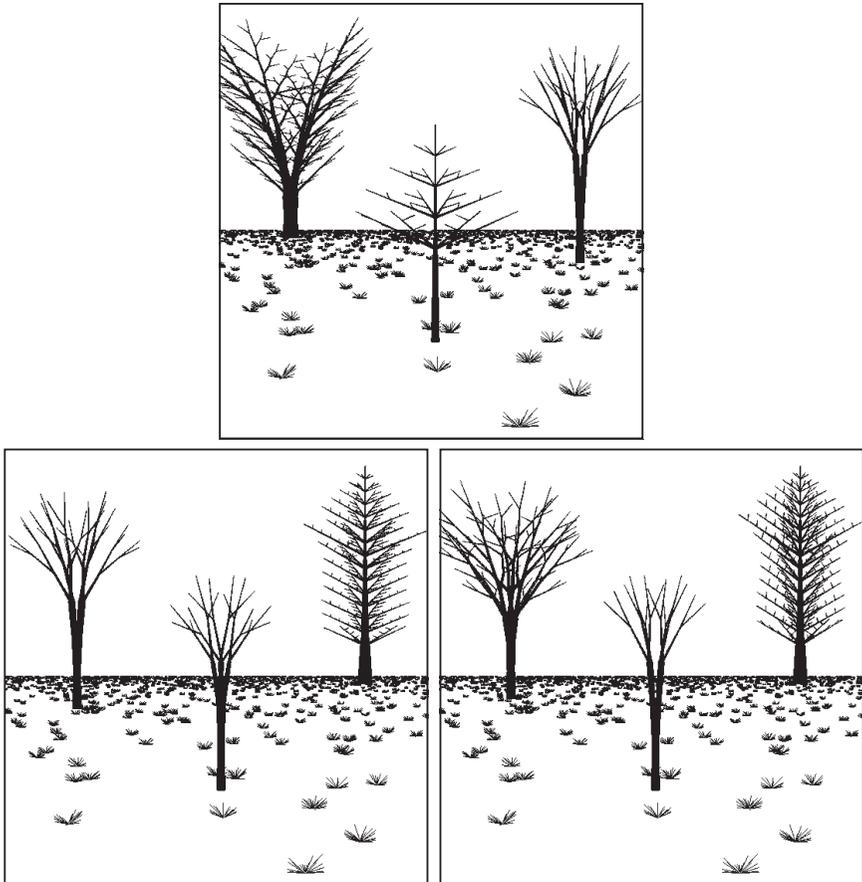
FIGURE 5   Examples of the small target trees in each of the three architectures all located along the ground texture gradient at an incorrect near location. The top panel is architecture P. The bottom left panel is architecture C. The bottom right panel is architecture V.

sequently called "informational bases" (Runeson & Frykholm, 1983). Shaw found his basis in allometry. He (and Runeson, too) showed that the abstract is ultimately very concrete, and this is the basis for meaning in information. What a marvelous idea this was, intuited by Gibson and fleshed out by Shaw and Runeson.

ACKNOWLEDGMENT

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