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Final Report

BEES AND POLARIZED LIGHT

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Von Frisch (1952, et al.) has demonstrated beyond doubt that bees can orient to the plane of polarization* of diffuse incident light. This ability is expressed in their dances, in which bees communicate to one another the direction of a food source. By using a piece of sky and altering its plane of polarization with a sheet of polaroid, von Frisch shows that the bees behave as though they read the sun to be approximately at right angles to this plane.

Since von Frisch first demonstrated this phenomenon, orientation to polarized light has been observed in other arthropods by a number of people, including the present authors.

After working with polarized light and a variety of aquatic arthropods for several years, we developed certain ideas regarding the underlying mechanism for detection, and eventually reached the point where we had questions to ask the bees. For these purposes a simple experimental design was necessary, in which bee behavior could be studied under a variety of conditions not always amenable to such complex behavior as bee language. Hence, a simple test was designed which could be applied to bees caught at random around the laboratory with a reasonable assurance of appropriate performance.

Bees, like many other arthropods, are usually positive to light when placed in a dark chamber. In these experiments bees were placed in a dark chamber 10 inches square and 1/4 inch deep (inside dimensions), and covered with clear glass. The chamber was placed in a darkroom and illuminated from above with a slightly divergent beam of white light of about 12-foot-candles intensity. One bee was used at a time. It could see only the overhead light and various reflections. The latter were reduced as far as possible. The floor of the chamber was a very black, dull paper; its sides were not only black but were shaded by black tape on the glass cover; the entire apparatus was abundantly shielded with black cloth.

An introduced bee usually did one of three things: it walked or ran rapidly back and forth as though trying to get out, it groomed itself, or it went to sleep. Data were collected only in the first instance, which occurred about one-third of the time.

When a polaroid was placed in front of the light, it was evident that bees tended to run back and forth at right angles to the plane of polarization, with occasional runs in other directions and a considerable amount of running along the edges. To score this behavior, two sets of lines at

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* I.e., plane of vibration of polarized light as checked by the use of a reflecting surface.

right angles to each other were added to the glass cover. One observer counted how often the bee crossed the lines of one set, while the other counted how often it crossed the lines of the other set, so that the bee path was analyzed into two vectors (left-right and front-rear). The lines of a set were one inch apart, and to eliminate the edge effect all lines ended one inch from the edge.

Once the bee was running well, a timer was started and both observers counted for a fixed time interval, usually two minutes. This was usually repeated, resulting in several trials for each bee. Results are shown in Table I.

TABLE I. RESULTS WITH BEES ON DULL BLACK PAPER
Data represent inches traveled in two vectors at right angles to each other during the same time interval. Within bees, variations between trials are not greater than random.

Bee	Trials	No Polaroid		Polaroid ≡		Polaroid |||	
		↔	↕	↔	↕	↔	↕
1	1	70*	69*	8*	25*	12*	9*
	2	77*	57*	22*	43*	111	38
	3	30*	35*	8*	15*	81	37
	4	48*	47*	34	75		
	Total	225	208	72	158	204	84
2	1	182	186	74	75	191	128
	2	114	87	99	119	177	114
	3			88	104		
	Total	296	273	261	298	368	242
3	1	93	77	57	111	119	55
	2	69	75	39	95	99	45
	Total	162	152	96	206	218	100
4	1	38	45	56	75	81	42
	2	57	52			52	31
	Total	95	97	56	75	133	73
5	1	92	86	52	84	50	22
	2	66	60	33	42	33	22
	Total	158	146	85	126	83	44

* Bee was upside down throughout reading.

In this first experiment the performance was first recorded without a polaroid, and then with the polaroid in two positions (parallel to each of the two sets of lines) so that accidental asymmetries in the environment could be ruled out. In the absence of a polaroid the two vectors were nearly equal, with some tendency to go left and right. With a polaroid the major vector was at right angles to the plane of polarization. (The position of the polaroid is indicated by the parallel lines in the column headings.) Variations from one trial to another for the same set-up and same bee are not greater than random.

One bee did most of its running upside down on the glass cover, and as shown it oriented about as well as the others. This was also true of later experiments. Such evidence argues against the ocelli as sources of information for this orientation.

On Table II the totals for each bee are reduced to percentages. Differences between bees are greater than random, showing that different bees orient to different degrees. The average for these five bees shows almost a 2-to-1 ratio for the vector at right angles to the plane of polarization. The slight tendency to travel left and right without a polaroid (51.4%) is significant, and this bias is apparently additive to the effect of the polaroid, for the two positions have significantly different effects (66.0% and 61.4%).

TABLE II. PERCENTAGE OF THE TRACK IN EACH OF THE TWO VECTORS, BASED ON THE TOTALS FOR EACH BEE FROM TABLE I

Differences between bees are much greater than random when a polaroid is used.

Bee	No Polaroid		Polaroid ≡		Polaroid ⦀		Avg. ⊥ to Polaroid		
	↔	↕	↔	↕	↔	↕	↙		
1	52	48	31	69	71	29	70.0	—	30.0
2	52	48	47	53	60	40	56.5	—	43.5
3	52	48	32	68	69	31	68.5	—	31.5
4	49	51	43	57	65	35	61.0	—	39.0
5	52	48	40	60	65	35	62.5	—	37.5
Avg.	51.4	48.6	38.6	61.4	66.0	34	63.7	—	36.3

Considering that bees must turn around frequently, and that they seldom run back and forth over exactly the same strip, these vectors have practical limits such that maximum orientation would not produce a ratio of 100 to 0. From the data of later experiments and from knowledge of similar behavior in aquatic arthropods, a ratio of 80 to 20 is extreme. On this basis the present orientation is good.

If the bees are orienting by a direct analysis of the plane of polarization in the incident light, the nature of the substrate should be of minor importance. Hence, the experiment was repeated on white paper, very white but not shiny. The results (Table III) show no average orientation at all to the plane of polarization. Individual bees, however, show varying degrees of positive and negative orientation. The fact that some are negative will be discussed again later.

TABLE III. RESULTS USING BEES ON DULL WHITE PAPER
The sample size (sum of both vectors) and percentage perpendicular to the plane of vibration of the polarized light are shown.

	Polaroid ≡		Polaroid ⫴		Average
Bee	Total Count	% ⊥ to pol.	Total Count	% ⊥ to pol.	⊥ to pol.
1	601	54	579	51	52.5
2	378	52	364	48	50.0
3	459	37	382	49	43.0
4	107	48	334	56	52.0
5	544	52	539	40	46.0
6	1227	54	1283	51	52.5
7	568	56	397	51	53.5
Avg.		50.4		49.4	49.93

It is possible, of course, that a large reflectance signal "drowns out" an analysis of polarization, and to check this the lower halves of the compound eyes of several bees were painted out. This was done carefully so that all ommatidia directed laterally or lower were covered, using a quick-drying aluminum lacquer. The results on white paper are shown in Table IV. The orientation is in no sense restored. Although both bees were negative they are not significantly different from the seven bees of Table III.

TABLE IV. SAME AS TABLE III, EXCEPT THAT THE LOWER HALVES OF THE COMPOUND EYES ARE PAINTED OVER SO THAT THE BEES SEE PRIMARILY UPWARD

	Polaroid ≡		Polaroid ⫴		Average
Bee	Total Count	% ⊥ to pol.	Total Count	% ⊥ to pol.	⊥ to pol.
1	414	47	483	48	47.5
2	312	49	605	47	48.0
Avg.		48.0		47.5	47.75

The next logical step, and one that had been anticipated before starting the experiments, was to place bees with the lower halves of the eyes painted on dull black paper. As shown in Table V, the bees showed no orientation. One of the bees (number 2) turned upside down and anticipated the next experiment, since it oriented (56%) in this position, although it did not when right side up.

TABLE V. LIKE TABLE IV, EXCEPT THAT THE BEES ARE ON DULL BLACK PAPER
The bees see primarily upward.

	Polaroid ≡		Polaroid ⦀		Average
Bee	Total Count	% ⊥ to pol.	Total Count	% ⊥ to pol.	⊥ to pol.
1	374	49	330	54	51.5
2	397	52	391	47	49.5
3	654	49	483	50	49.5
Avg.		50.0		50.3	50.15
2 (upside down)	146	56	146	56	56.0

When the upper halves of the eyes were blinded (Table VI) the bees orient a little more than half as well as normal bees. Such bees have an obvious behavioral disturbance and turn more frequently than normal bees, so that these records are about as good as could be expected.

TABLE VI. BEES WITH THE UPPER HALVES OF THE EYES PAINTED OUT, ON DULL BLACK PAPER
Data same as in Tables III-V.

	Polaroid ≡		Polaroid ⦀		Average
Bee	Total Count	% ⊥ to pol.	Total Count	% ⊥ to pol.	⊥ to pol.
1	281	67	82	54	60.5
2	215	59	718	54	56.5
3	307	60	360	57	58.5
4	321	57	307	54	55.5
Avg.		60.75		54.75	57.75

The implication of the two eye-painting experiments is that the observed orientation of normal bees is due entirely to cues received from below, and not directly from the incident light.

The reflectance of the substrate was examined (Fig. 1) using a photocell collimated to receive a solid angle of about 3° (the same as is supposed for the bee ommatidium) and aimed at the paper along various sighting angles. The paper showed a slight structural grain, and one set of sightings was taken parallel to the grain, the other at right angles (front-rear and left-right in the original setup). The grain in the paper produces a small bias, so that without a polaroid more light is reflected left-right than front-rear. The effect of this paper bias appears to be added to the effect of a polaroid, for the brightness disparity between the two axes is greater with the polaroid parallel to the grain than at right angles to it (compare right and left figures). In all three cases the bees tend to run in the axis of greater intensity of reflected light, and this orientation was best for the setup producing the right-hand graph.

Some of this paper was sprayed with a clear, liquid plastic that dried to form a light gloss. As a result, the high angle reflectance (Fig. 2) was increased and the low angle reflectance decreased, but the latter were more selected than before. The bias increased considerably, so that when it is opposed to the effect of the polaroid (center graph) the brightness bias is about the same (although in the opposite axis) as that of the paper without a polaroid. The bias becomes very large when the two effects coincide (right).

The performance of bees on this surface is shown in Table VII. The degree of orientation is about the same without a polaroid and with the polaroid opposed to the grain (compare left and right columns), and is much greater when the two effects are added (center columns).

TABLE VII. NORMAL BEES ON BLACK PAPER SPRAYED WITH PLASTIC TO INCREASE REFLECTION BIAS

Data shown are the total counts and the percentage in each of the two vectors for each bee.

Bee	No Polaroid			Polaroid ≡			Polaroid ‖		
	Total Count	% ↔	↕	Total Count	% ↔	↕	Total Count	% ↔	↕
1	587	46	- 54	723	36	- 64	600	62	- 38
2	458	41	- 59	611	27	- 73	409	54	- 46
3	141	44	- 56	237	29	- 71	167	60	- 40
4	269	47	- 53	241	48	- 52	127	46	- 54
Avg. Omitting 4		43.7	- 56.3		30.7	- 69.3		58.7	- 41.3

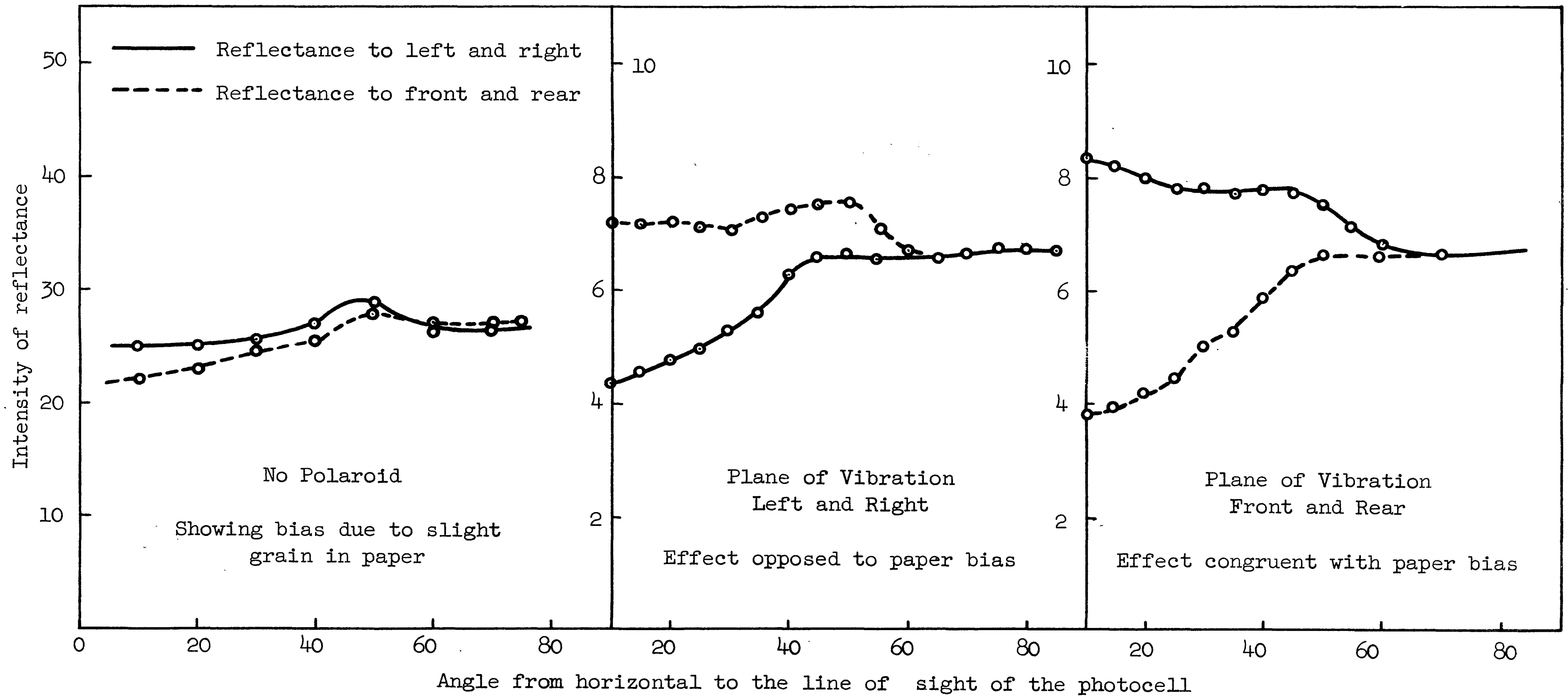

Fig. 1. Reflectance patterns from dull black paper in photometer units at various angles with the paper surface. The light source is a slightly divergent beam perpendicular to the paper. In the middle and right figures a polaroid is inserted close to the light source.

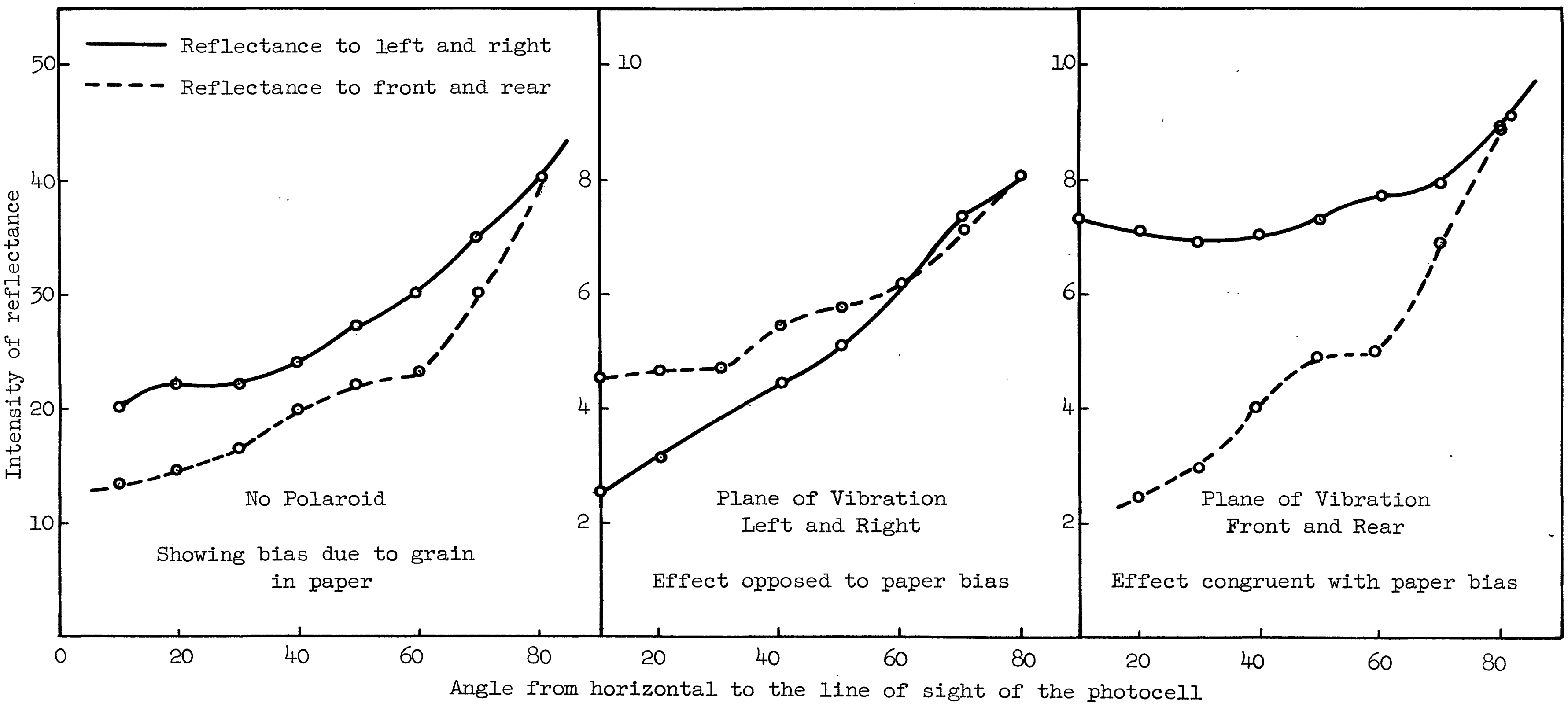

Fig. 2. Reflectance patterns from dull black paper sprayed with clear plastic. Photometer units are comparable with those of Fig. 1, and show an increased reflectance at high angles but a decreased reflectance at low angles. The paper bias is increased.

In this experiment one bee (number 4) was found whose behavior was insensitive to the setup and did not vary. This is the only such bee that has been found, and it is not included in later summaries.

Since the brightness pattern of the reflectance is obviously important, a method for estimating the bias was devised (Table VIII). For each sighting angle between 10° and 40°, the reflectance in the major axis was expressed as a percentage of the sum for both axes, and the average of these four percentages found. This is taken as an index of the reflectance bias.

TABLE VIII. PERCENTAGE OF REFLECTANCE IN THE MAJOR DIRECTION AT VARIOUS ANGLES OF ELEVATION FOR THE PHOTOCELL, USING VARIOUS SURFACES

Angle	No Polaroid		Polaroid - Bias		Polaroid + Bias		Pol. on Dull White
	Dull Black	Sprayed Black	Dull Black	Sprayed Black	Dull Black	Sprayed Black	
10°	53.2	59.7	62.6	64.3	69.2	80.1	52.0
20°	52.1	60.3	61.4	59.4	67.5	74.7	50.8
30°	51.0	57.1	60.0	55.3	65.6	69.7	49.8
40°	51.5	54.6	58.7	55.2	63.7	63.6	50.1
Avg.	52.0	57.9	60.9	58.6	66.5	72.3	50.5

When the bias is compared with bee orientation (Table IX), it is evident that the two are closely related and that reflectance bias becomes an adequate explanation for the observed orientation.

TABLE IX. COMPARISON OF REFLECTANCE BIAS (FROM TABLE VIII) AND BEE ORIENTATION

Surface	Reflectance	Bees
White paper plus polaroid	50.5	49.9
Dull black paper, no polaroid	52.0	51.4
Sprayed black paper, no polaroid	57.9	56.3
Sprayed black, polaroid opposed to paper bias	58.6	58.7
Dull black, polaroid opposed to paper bias	60.9	61.4
Dull black, polaroid and paper bias together	66.5	66.0
Sprayed black, polaroid and paper bias together	72.3	69.3

Polarization itself, however, has not necessarily been ruled out. Light from dark paper is polarized after reflection whether it was before or not, and it remains possible that this light must be polarized for a proper response. A variety of different experiments were designed as critical tests of this point and as further checks on a direct analysis of incident light.

A mirror (Table X) offers an interesting substrate, for the reflection is bright and strongly polarized in the original plane, but has little brightness bias. Bees orient about 30% as well on the mirror as they do on dull black paper, although the polarization signal is doubled. This is a critical experiment that should be repeated on other organisms.

TABLE X. RESULTS WITH BEES ON A CLEAN MIRROR SURFACE WITH EXTRANEOUS REFLECTIONS REDUCED AS FAR AS POSSIBLE, AND CONTROL EXPERIMENTS WITH THE SAME BEES ON DULL BLACK PAPER

Data shown are total counts and the percentages perpendicular to the plane of vibration of the light.

Bee	Mirror					Paper					Ratio of
	Polar. ≡		Polar. ⫴		Avg.	Polar. ≡		Polar. ⫴		Avg.	Mir.%-50
	No.	%	No.	%	%	No.	%	No.	%	%	Pap.%-50
1	428	52	525	51	51.5	433	70	433	61	65.5	0.097
2	690	55	597	51	53.0	372	65	543	58	61.5	0.260
3	486	56	446	51	53.5	384	66	384	59	62.5	0.280
4	311	56	258	54	55.0	417	59	372	56	57.5	0.667
Avg.					53.3					61.2	0.295

A "quarter-wave plate" (Table XI) was also used. When "Scotch Tape" is mounted at 45° to the plane of polarization, the plane polarized light is broken into various elliptical patterns dependent on the wavelength. (For red light the ellipse is long and narrow with a long axis at 90° to the former plane of polarization; for green light the ellipse is circular; for blue light the ellipse is broad with a long axis the same as the former plane of polarization.) The over-all effect is a weak polarization at 90° to the original plane of polarization.

When the entire chamber is covered with tape ("general plate" in Table XI) the orientation of the bees is reversed (left) or much reduced (right). In the latter case the new weak polarization fails to overcome the paper bias. In both cases, however, the vector perpendicular to the original polaroid is reduced about 20 percentiles by the tape.

In the critical experiment a 1-inch square of tape was mounted on the end of a fine wire and held over the bee at 45° to the plane of polarization. Although it is difficult to keep the tape centered exactly over the bee, its head was never allowed to be uncovered. On the average the light affected was not only all of that directly incident on the bee but also that reflecting from the substrate out to sighting angles of about 40°. It is evident from Table XI ("local plate") that this treatment had astonishingly little effect, considering the possible disturbances involved. Thus, directly incident light and high-angle reflections are both ruled out as significant factors in this behavior. This is another critical experiment that should be repeated on other organisms.

TABLE XI. EXPERIMENTS WITH A QUARTER WAVE PLATE OVER SPRAYED BLACK PAPER

One bee. Actual counts in both vectors are shown, together with totals and percentages at the bottom. The "local plate" is a 1-inch square held over the bee as it moved; the "general plate" is a 12-inch square covering the entire chamber.

	Polaroid ≡			Polaroid ⦀		
Trial	No Plate	Local Plate	General Pl.	No Plate	Local Plate	General Pl.
	↔ ↕	↔ ↕	↔ ↕	↔ ↕	↔ ↕	↔ ↕
1	132 - 72	107 - 57	69 - 102	46 - 124	53 - 137	85 - 108
2	129 - 67	102 - 65	65 - 91	46 - 135	48 - 120	96 - 114
3	129 - 64	53 - 35	58 - 75	45 - 150		55 - 63
4	70 - 55			34 - 98		74 - 98
5	73 - 56			44 - 125		64 - 76
6	69 - 43			33 - 80		
Total	602 357	262 157	191 268	248 712	101 257	374 459
%	63 - 37	62 - 38	42 - 58	26 - 74	28 - 72	45 - 55
Change of %		- 1	- 21		- 2	- 19

Two attempts were made to provide the bee with a surface so biased in its reflection that opposed polaroids are overwhelmed. In one case mirrors were mounted on opposite sides so as to reflect the overhead light onto the paper. The reflectance bias was about 88%. With the polaroid in its two positions the bias remained in the mirror axis at 91% and 70%. Bees under these conditions oriented 71%, 76%, and 66%, respectively.

A smooth surface of norite-blackened beeswax was carefully brushed in one direction with a wire brush. The resulting grain had a reflectance bias of 89.7% without a polaroid, 92.4% and 76.8% in the same axis with a polaroid. Bees oriented to this axis at 66.3%, 67%, and 61.3%, respectively. Because the reflectance of black wax is high and reflected secondarily from the glass cover, these bees had the top halves of their eyes painted out.

All these data are gathered together in Fig. 3, where bee orientation is plotted against reflectance bias. Each surface is identified with a letter and is defined in Table XII. Normal bees appear to have a maximum orientation at about 75%, while those with the upper halves of the eyes painted behave one-half to two-thirds as well. If the location of the

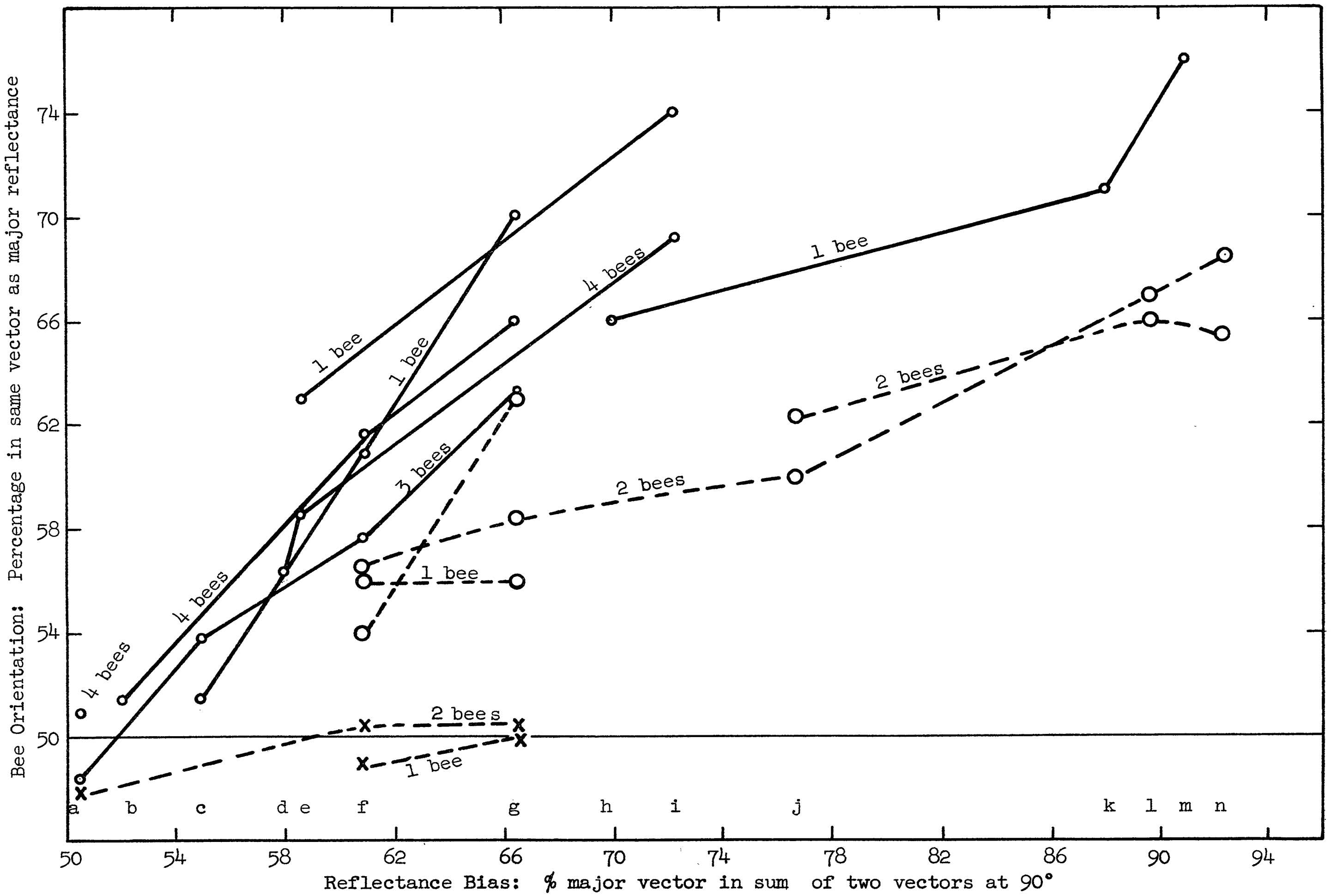

Fig. 3. Relation of bee orientation to the reflectance patterns of various surfaces (a to n).

Solid lines: Normal bees.

Open circles: Bees with the upper halves of compound eyes painted out.

Crosses: Bees with the lower halves of compound eyes painted out.

Crosses in circles: Like crosses except that bee was upside down throughout readings.

TABLE XII. SUMMARY OF THE VARIOUS SURFACES USED IN FIG. 3, SHOWING THAT REFLECTANCE BRIGHTNESS BIAS ALONE EXPLAINS MOST OF THE REPONSE

Surfaces without Overhead Polaroid:
- b. Dull black paper, slight grain bias.
- d. Sprayed black paper, moderate grain bias.
- k. Sprayed black paper with side mirrors reflecting onto paper, strong bias.
- l. Black wax with fine parallel scratches, strong grain bias.

Surfaces with Polaroid which Is Major Factor Determining Reflectance Bias:
- a. White paper, slight brightness bias on top of general depolarized reflection.
- c. Clean mirror, slight brightness bias on top of bright, fully polarized reflection.
- e. Sprayed black paper, polaroid effect reduced by opposed grain bias.
- f. Dull black paper, polaroid effect reduced by opposed grain bias.
- g. Dull black paper, polarization effect increased by congruent grain bias.
- i. Sprayed black paper, polarization effect increased by congruent grain bias.

Surfaces with Polaroid which Is a Minor Factor Congruent with Major Factor:
- m. Sprayed black paper with side mirrors, effect increased by polaroid.
- n. Scratched black wax, grain effect increased by polaroid.

Surfaces with Polaroid which Is a Minor Factor Overruled by Major Factor:
- h. Sprayed black paper with side mirrors, effect reduced by opposed polaroid.
- j. Scratched black wax, grain effect reduced by opposed polaroid.

various kinds of surfaces are studied, it becomes apparent that no class produces data following a different trend. Hence, it is concluded that bias in the brightness of the reflectance pattern contains all the information used by the bees in this behavior. Polarization itself is not analyzed.

As a final experiment, a film of white paraffin was placed over the compound eyes. Such a film, about 0.2 mm thick, transmits tolerably well but almost completely depolarizes incident light. The initial results (Fig. 4, open circles) were surprising, since the orientation is clearly negative for substrates with a low reflectance bias. It was then discovered that the brightness of light transmitted through a paraffin film that is illuminated obliquely on the other side is sensitive to the plane of polarization, but opposite to the effect of reflection. That is, the transmitted light was brightest when the observer looked in the axis of the plane of polarization rather than at right angles to it.

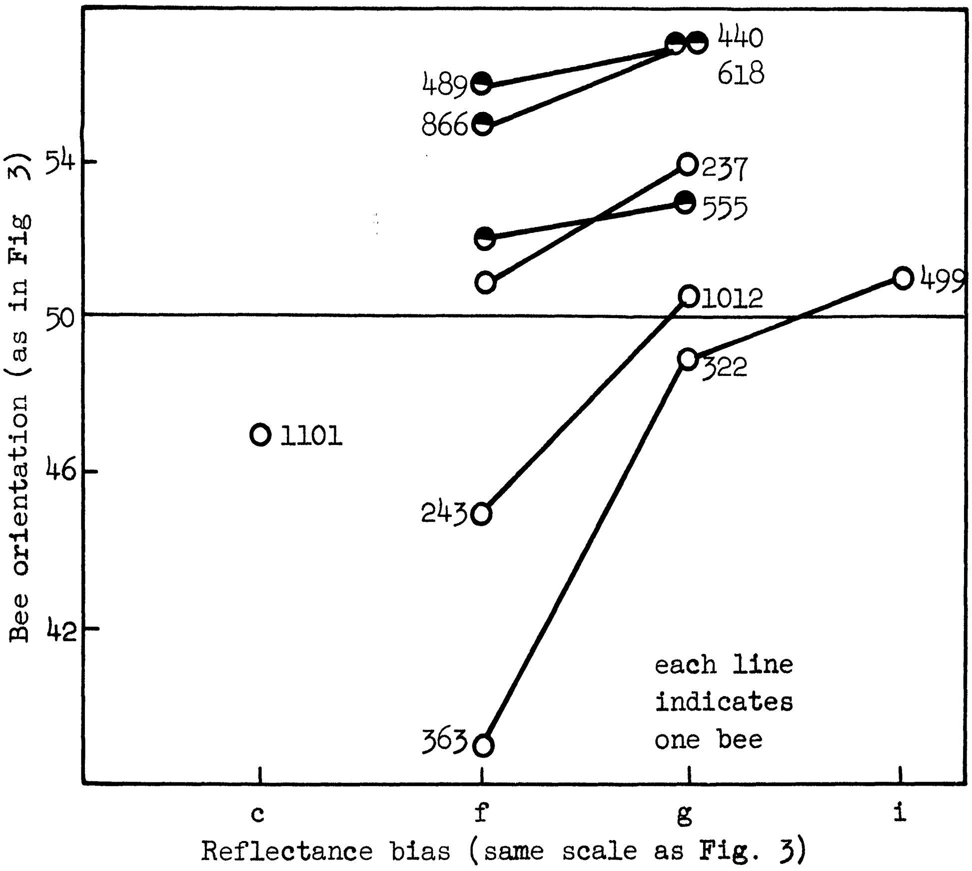

Fig. 4. Results with bees having a depolarizing film of white paraffin over the compound eyes.
Open circles: Both eyes completely covered with paraffin.
Half black circles: Upper halves of eyes painted black, lower halves covered with paraffin.

To overcome this effect of the direct illumination, bees were prepared with the upper halves of the eyes painted with aluminum lacquer and the lower halves covered with paraffin. Such bees (half black circles on Fig. 4) behave about one-fourth as well as normal bees, or half as well as bees with paint but without paraffin. That bees so treated have any visual acuity left at all is surprising enough, and little support is left for a role of polarization.

We would now like to show two things further: (1) that reflectance patterns with adequate bias are present in the experiments of von Frisch; and (2) that orientation to the reflectance-scatter pattern is a simpler explanation of the behavior than response to polarization directly.

Accordingly, we can now pass to the actual lighting conditions of von Frisch's experiments. To duplicate the geometry of his experimental conditions, we placed a brood comb in a horizontal position in front of a north window. It was illuminated by the north sky from 30 to 60° of altitude and about 40° of azimuth. A sheet of polaroid matching the polarization of the sky was superimposed on the comb.

Since we wished to see the reflectance-scatter pattern visible to a bee's eye we took a bee's eye view of the comb by poking a periscope up through a small hole in the comb. The periscope was rotatable in 360° of azimuth and adjustable in the angle of view of the substrate. A photomultiplier looked into the periscope to measure the intensity of reflectance and scatter. The light intensity reflected and scattered for a 10° sighting angle is plotted on polar coordinates in Fig. 5. The arrows indicate the plane of polarization of the incident light on the brood comb. In general the pattern is elliptical and the long axis points at the sun.

By altering the sighting angle of the periscope to 30° and repeating the measurements at every 15° of azimuth, one obtains the reflectance scatter diagrams seen in Fig. 6. The arrows indicate the plane of polarization of the incident light. The long axes of the patterns are still discernible except in the case of a north-south plane of polarization. We shall say more about this pattern later.

Since the bee moves about freely and sees all aspects of the comb, it is important to know whether different orientations of the comb relative to the incident light will change the appearance of the reflectance scatter pattern. Figure 7 shows reflectance-scatter intensity plots of a 10° sighting angle at the brood comb in four different positions, each rotated 90° from the preceding. This demonstrates that the larger geometry of the brood comb has little effect on the reflectance-scatter pattern.

It is also important to know the effect of other bees on the reflectance-scatter pattern. This is seen in Fig. 8, where the field of view of the periscope was almost completely covered with bees. Arrows indicate the plane of vibration of the incident light. Although this is somewhat different from Fig. 5, the patterns are recognizable. It should be pointed out that the bees used here were dead and may have failed to reflect light like live bees.

With certain exceptions the published data of von Frisch concern the behavior of bees with the superimposed plane of polarization at right angles to the direction of the sky used or at 10 or 20° from this position. The reflectance-scatter patterns for these positions of the polaroid are seen in Fig. 9.

Regarding simplicity of postulates, it is already known that bees are positively phototactic and have considerable ability to discriminate slight

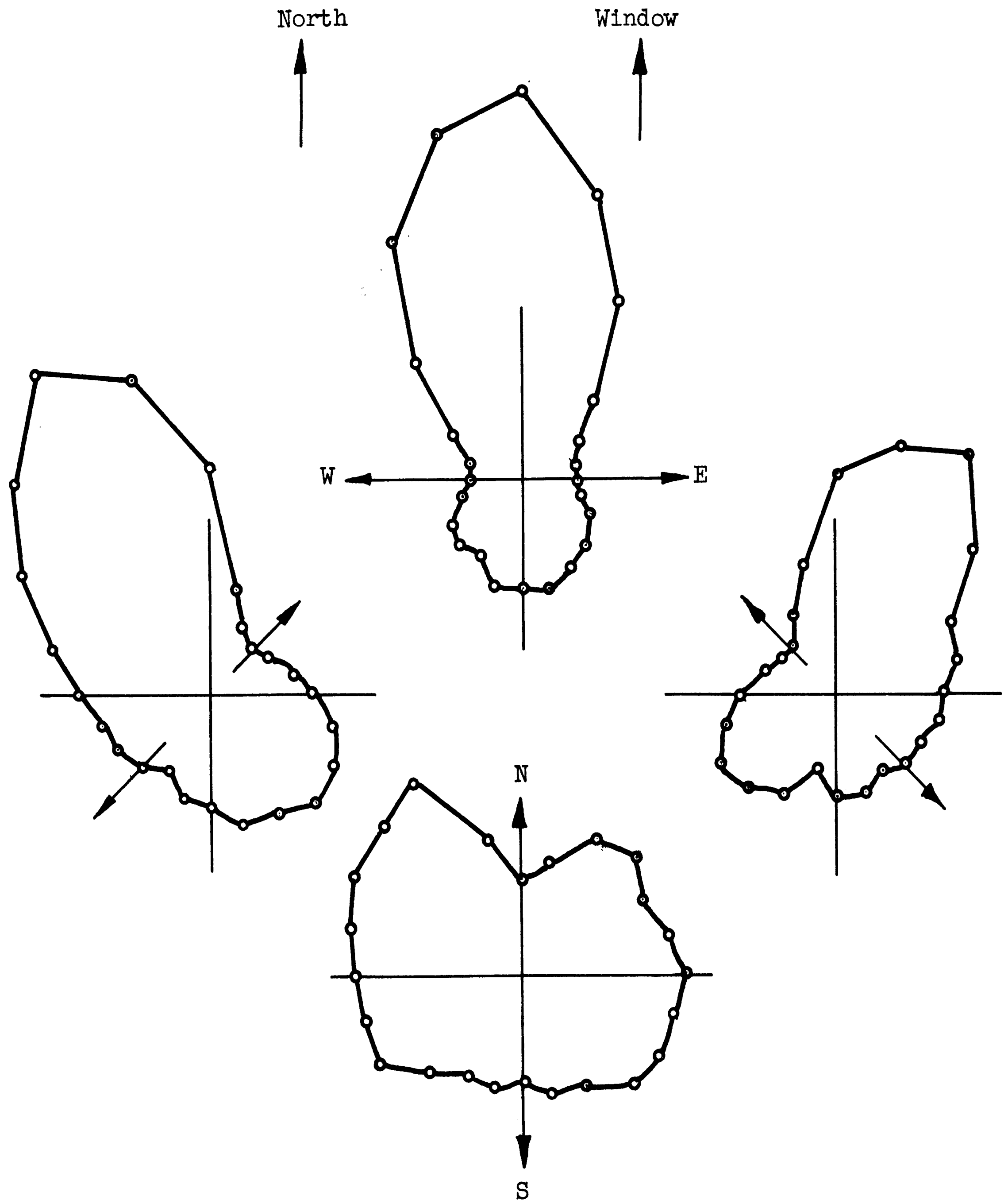

Fig. 5. Reflectance patterns from a brood comb at a sighting angle of 10°. Readings were taken with the polaroid in four different positions as indicated by the arrows, showing the effect of the plane of polarization on the pattern. Averages of three readings with the comb in one position.

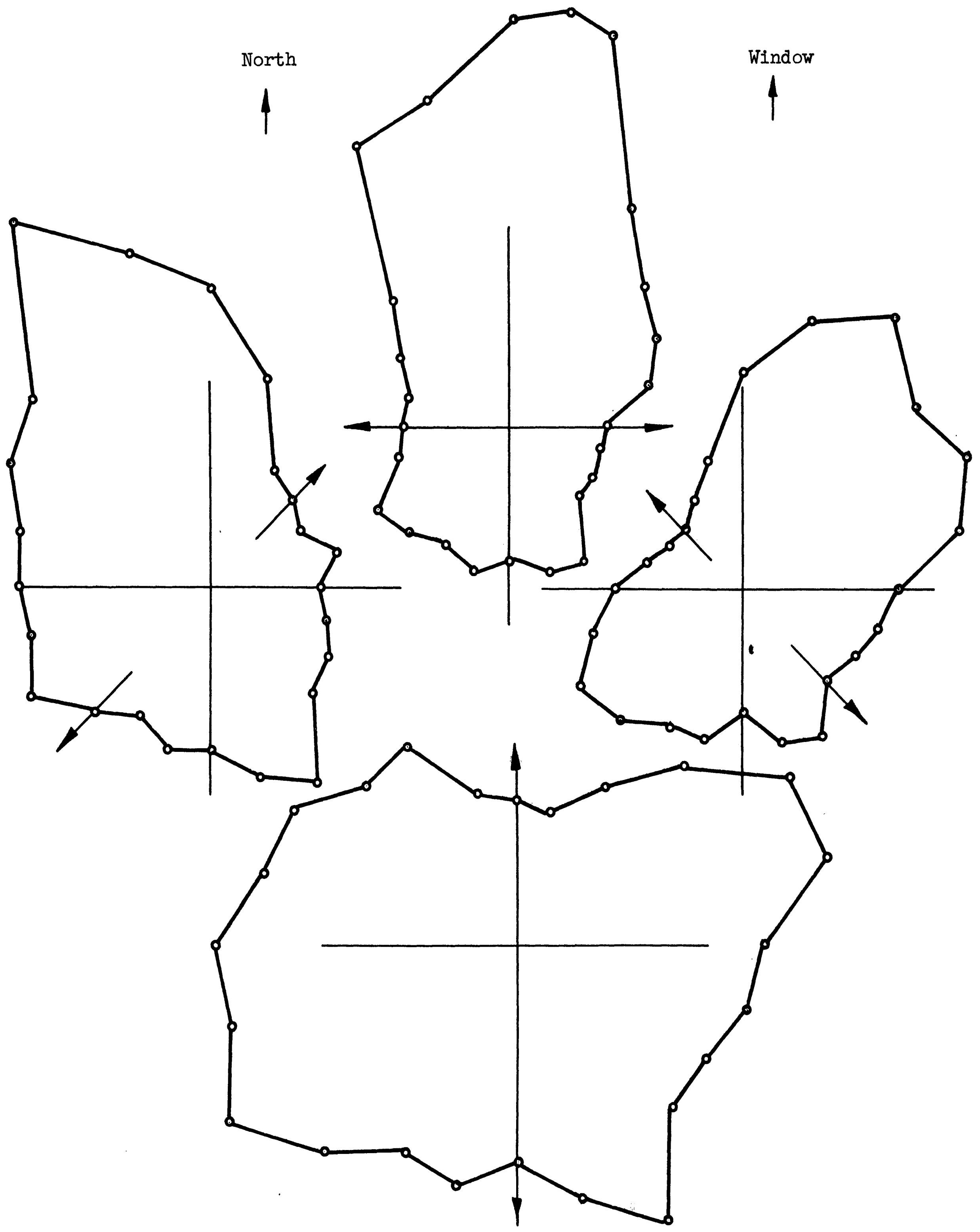

Fig. 6. Reflectance patterns from a brood comb at a sighting angle of 30°. Polaroid in four different positions, as shown by arrows.

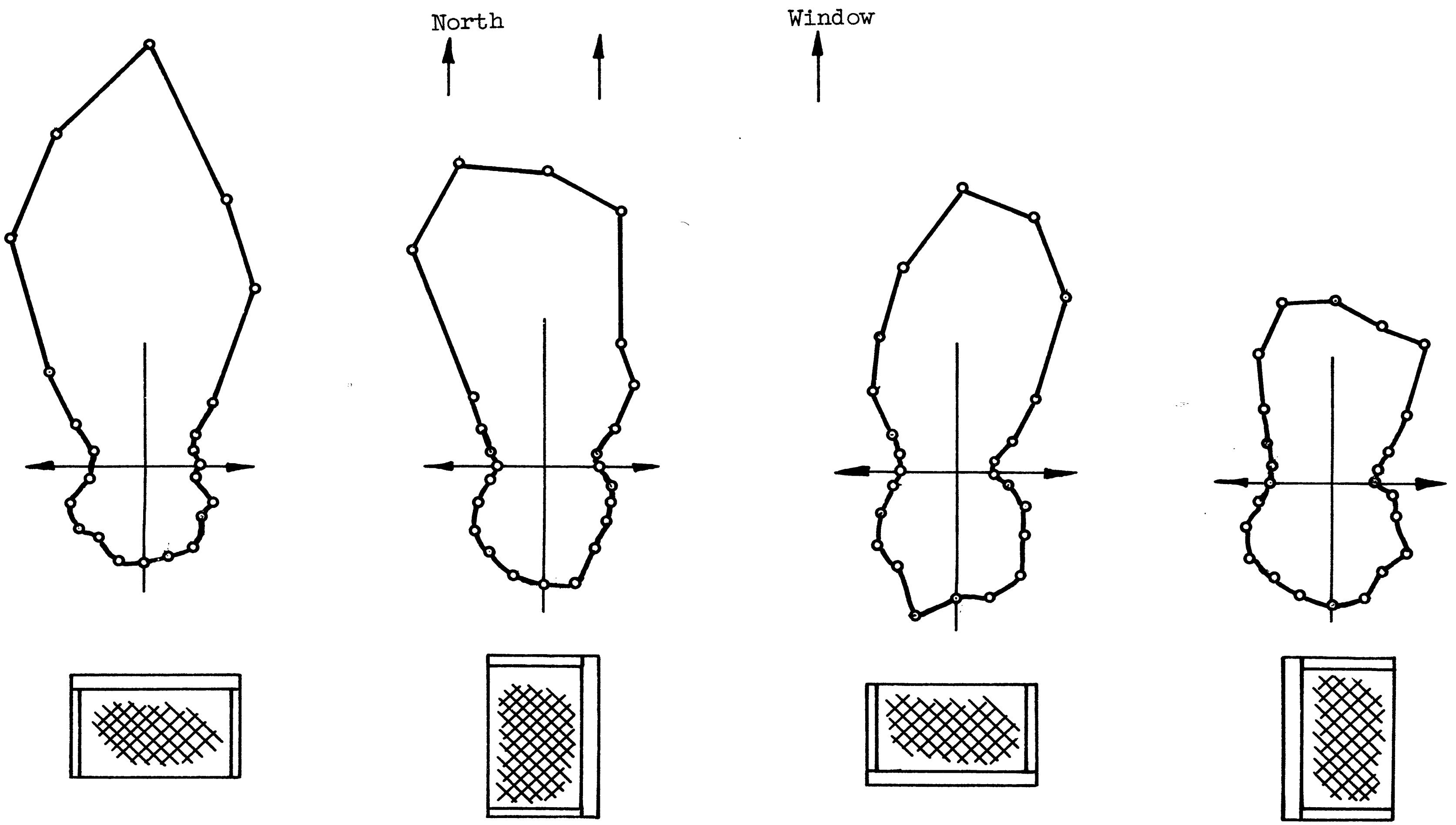

Fig. 7. Reflectance patterns from a brood comb at a sighting angle of 10°. Light source a piece of north sky. Polaroid sheet over brood comb with the plane of polarization east-west as shown by the arrows. The pattern was recorded with the comb in four different positions, successively rotated 90° clockwise as shown in lower figures. The stability of the basic pattern exceeds the effect of local irregularities. Data are plotted as polar coordinates with intensity as distance from the origin.

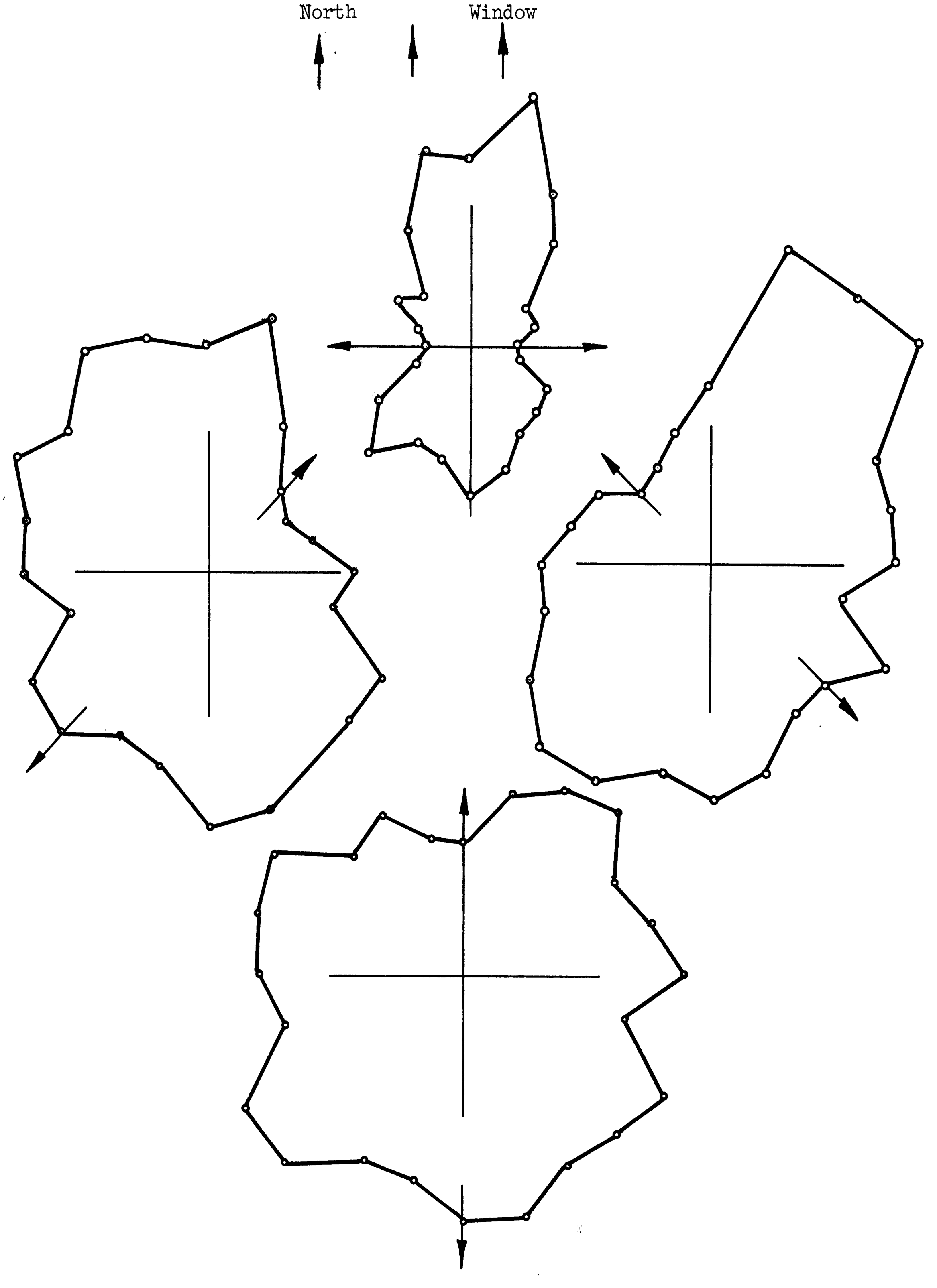

Fig. 8. Like Fig. 5, except that 38 dead bees have been placed on the field of vision. In spite of greater reflectance, the basic patterns are preserved.

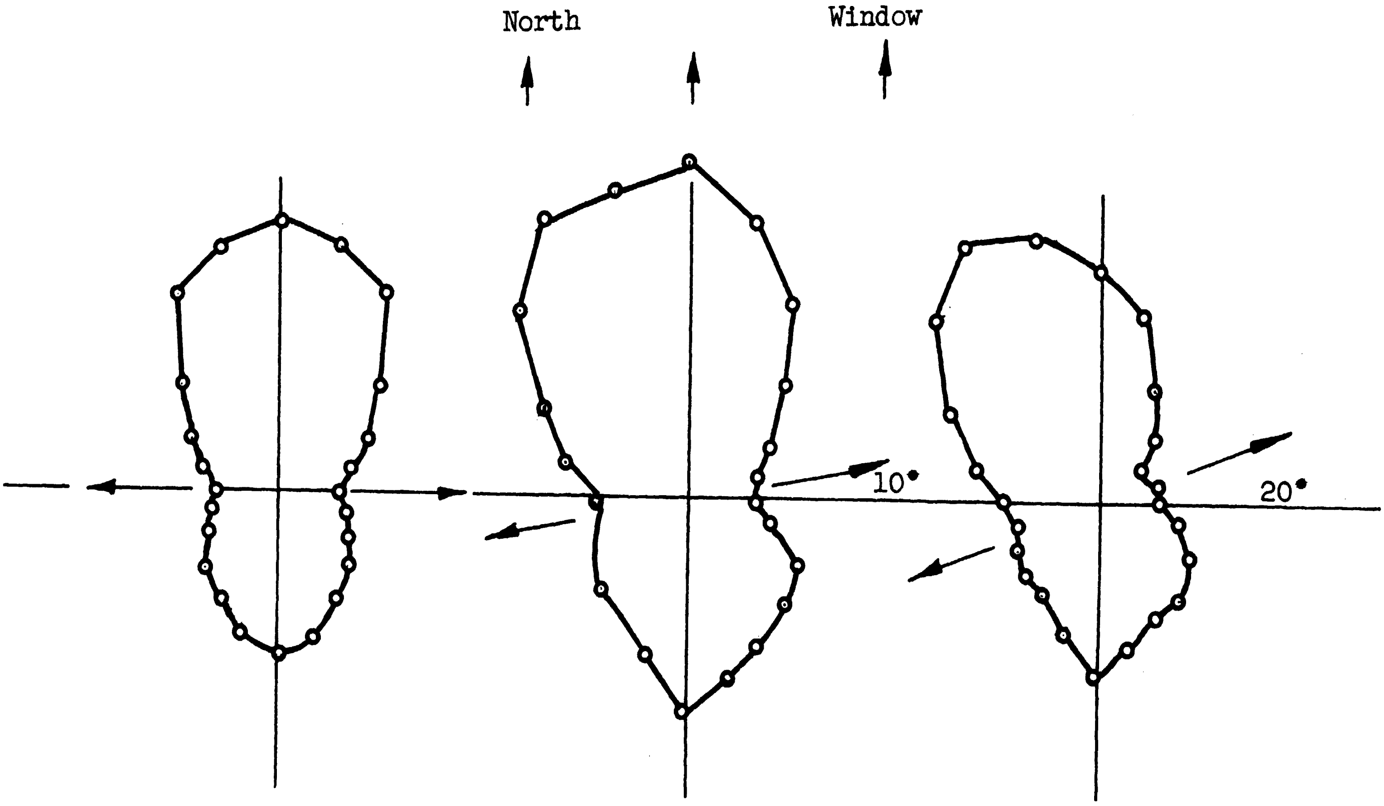

Fig. 9. Reflectance patterns from a brood comb at a sighting angle of 10°, showing the effect of small deviations from east-west in the position of the polaroid. Each point is an average of two readings for each of two positions. The southward points in the center and right figures represent obvious comb irregularities.

brightness differences. It is no great step from discrimination of brightness differences to recognition of relatively uncomplicated scatter-reflectance patterns with their long axes indicating the position of the sun. Further, it has been shown that the bee has an effective clock. If the position of the sun and the time of day are known, it is possible to indicate a compass course toward any desired object. This would appear to be a simpler explanation of the observed behavior patterns than having the bee remember the entire polarization pattern of the sky for all hours of the day for several days as is necessary for von Frisch to explain his results on cloudy days.

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