Witt, P. N., *et al.* 1977. Spider web-building in outer space: evaluation of records from the Skylab spider experiment. J. Arachnol. 4:115-124.

SPIDER WEB-BUILDING IN OUTER SPACE: EVALUATION OF RECORDS FROM THE SKYLAB SPIDER EXPERIMENT

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ABSTRACT

Two spiders built orb-webs in Skylab under zero gravity only four days after release from transportation vials. The first webs resembled pre-flight controls in size and regularity, but the unusual distribution of radial angles and thinness of thread together with a probably low number of turning points in the spiral indicated a deviation from earth webs which can be attributed to the absence of gravity as a cue. Other web changes like a gradual decrease in regularity, diminished web size, and the spiders' decrease in body weight are identified as being likely consequences of starvation, Skylab stress and unknown circumstances not directly connected with zero gravity.

INTRODUCTION

Evaluation of measurements taken from the photographs of a spider web provides detailed information on the animal's behavior during web construction for a period of about 30 minutes. Extraordinary circumstances like changes in the environment influence behavior and are reflected in web measurements (Witt, *et al.*, 1968). The photographic record shows that web parameters are sufficiently constant to make measurements predictable for an individual, and it contains enough detail to show the consequences of environmental stress on the builder. Such considerations prompted one of the authors (P.N.W.) to respond to an invitation from the National Aeronautics and Space Administration in 1968 to propose a project for the Biosatellite Program entitled "Effects of weightlessness on web-building behavior of spiders." It was suggested that spiders be sent into space, and that after their return to earth their web-building capability would be

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carefully compared to pre-flight webs. In a second experiment actual photography of webs built in a space-laboratory would be performed, and the photographs evaluated in comparison with earth webs. The Biosatellite Program was not flown.

Conditions beyond these laboratories' control led to the adoption of a prize-winning proposal by Judith Miles, a high school student from Lexington, Massachusetts, in 1972 to incorporate a spider web-building project into plans for Skylab II; she had read about our spider-web measurements in the National Geographic (Zahl, 1971). She submitted a proposal for an experiment as an entry in the NASA Skylab Student Experiment Competition. Her proposal was selected by a panel of National Science Teacher Association judges as one of the experiments which they recommended for NASA for flight in Skylab. We provided instructions to NASA scientists and J. Miles, but were no longer directly involved in the planning process.

In May of 1972 we had an opportunity of evaluating web-photographs of two spiders, which had been subjected at the Marshall Space Flight Center to vibration and "Skylab atmosphere (70% 0_2 30% N_2)," in simulation of non-gravity stress factors during launch. For spider No. 1 four photographs of webs built directly before the experiment were compared with the measures of three webs built shortly thereafter; for spider No. 2 three webs before and six webs after the experiment were measured. We found no consistent, statistically significant change in 27 web parameters, covering size, shape regularity and web fine-structure.

When the Apollo spacecraft with three astronauts was launched on 28 July 1973, two spiders in small vials together with two flies were carried along. The first spider was released into a frame which would permit web-building in Skylab on 4 August, the second spider was released on 23 August 1973. At that time we had an opportunity to watch TV pictures of the two spiders. Finally, in April of 1975 we received a package from NASA with flight protocols and photographs of spiders, webs and threads. Mainly the evaluation of the material in the package is the subject of the following report.

MATERIALS AND METHODS

Web measurements: A protractor centered on the hub of the web was laid over each picture; a ruler with a notch at 0 mm could turn around the center of the protractor. Each point where thread touched thread could thereby be defined in polar coordinates. The figures for a reduced number of measuring points (about 10% of actual number) were fed into a computer, which was programmed to print out 27 web measures, defining the structure's regularity, shape, size and fine structure. For more information on web measurements see Witt, *et al.*, 1968. Where only incomplete measures were available, the evaluation was done without computer, using as many points as could be identified.

There were five pre-flight web photographs available for evaluation, four built by spider 1, one built by spider 2; all but one picture showed such low contrast that we were unable to obtain a complete set of web measures. In order to increase the number of control measurements, we added to the one measurable NASA web photograph five photographs from webs built by spiders of comparable age, body weight and species in our laboratory. An overlay of transparencies of one set of photographs onto the pre-flight webs, and statistical comparison of obtainable measurements, showed no recognizable differences between the pre-flight controls and our laboratory webs.

There were five in-flight webs photographed, each of which was incompletely recognizable. Only the radial angles and some spiral distances could be measured with some degree able. On the radial angles and some spiral distances could be measured with some degree of accuracy. Angle regularity and distribution of size of neighboring angles as well as spiral spacing in one or two directions could be used for statistical comparison. In one web, which does not appear on a photograph, the astronauts reported the number of radii and spiral turns.

On visual inspection, there was one apparently very regularly spaced web (angle and spiral turns); this is the second web built in flight by spider 1. The other four show all the characteristics of an *Araneus* web, like hub, radii, spiral and frame; but they were of small size and highly irregular spacing, somewhat comparable to webs built after a medium dose of d-amphetamine (Witt, 1971).

Web size could not be determined, because scale and periphery of webs were not on the photographs.

Thread thickness was shown earlier (Christiansen, *et al.*, 1962) to be dependent on the weight of the builder. A number of close-up photographs (400-2000x) of pieces of thread were available for both spiders, pre-flight and skylab. Unfortunately it was not possible to identify the type of threads with any certainty, but the astronauts reported that the web material they collected was from a regular web. Certainly there is no evidence that material from the sticky spiral was involved, since no glue droplets could be seen. The thickness was measured by one of us (D.B.P.) on the photographs.

A special question was whether the absence of gravity would do away with the commonly observed difference between angle size North and angle size South. The comparison was carried out in graphic and statistical format between the one regular in-flight web and the clearest pre-flight control.

At the end of August, 1973 the television news showed a short record of movements of both spiders, after spider 1 had been in the frame for several weeks and spider 2 had just been released. Through the courtesy of the Durham, North Carolina CBS station we were able to see the film segment many times and observe the animals' movements. Subjective evaluation of these observations was included.

RESULTS

The clearest, and in our opinion most important result is the photographic and observational evidence that both *Araneus diadematus* built several orb webs in Skylab, essentially under weightless conditions. One of these webs, which was built by spider 1 six days after release into the cage and 14 days after launch, looks on first inspection similar to pre-flight control webs. This indicates that the animals were able to pull threads out of the spinnerets and space the threads with their legs according to accustomed patterns of behavior (Figs. 1 and 2). The spiders continued to build a trap for flying prey under the very strange conditions of Skylab.

Measurements of radial angles reveals that in the one regular web radii were neither more regularly spaced than in controls nor significantly more irregular. However, Fig. 3 shows that the distribution of angle size is unusual in flight: while on earth most wide angles are in the top or Northern part of the web and most narrow angles in the lower part or South, the Skylab web shows about equal distribution in all sections. The range was between 8° and 25° in the pre-flight web, with a mean angle size of pre-flight control North 15.58, pre-flight control South 11.53; in-flight the range was between 8° and 23°, North 15.75, South 14.25. It appears that, lacking the cue from gravity, the web lost its North-South asymmetry.

Fig. 1.–NASA photograph of web built by an adult female *Araneus diadematus* Cl. spider in the pre-flight simulation experiment. The picture shows all the characteristics of the adult web of the species; note particularly the North/South asymmetry in the radial angle size and spiral distances, and the turning points in the spiral (arrow), which indicate the places where the web-building spider reversed directions.

Spiral size could not be measured, because the photographs do not show the outermost turns. A figure for spiral regularity can be established for pre-flight controls, and separately for the one regular in-flight web and other in-flight webs. Where there were no reference scales, the spiders of known size could be used for projecting web photographs to original size. In five pre-flight webs the spiral regularity was calculated at 0.390 ± 0.093 West and 0.403 ± 0.033 East. This means that distances between spiral turns varied less than 0.5 mm, indicating relatively regular spacing of consecutive spiral turns. In the one regular in-flight web the corresponding figures are 0.333 in the West and 0.69 in the East; there is no significant difference between the two sets of webs (Fig. 2). One of the irregular in-flight webs (Fig. 4) was measured showing a mean spiral regularity of 0.70 West and 0.96 East, which is significantly different from pre-flight and regular in-flight below the 5% probability level: this in-flight web had a spiral less regular than controls.

In looking at Fig. 2 another interesting difference appears between the regular in-flight web and pre-flight controls: while there are no turning points in the piece of spiral in the figure which was built in-flight, there are several in the pre-flight control (compare also Fig. 1). This difference is less conspicuous when the whole webs are inspected: in very few places where photographic contrast permits recognition of sufficient detail, turning points can be identified in pictures taken in flight. However, it can be stated with some confidence, but without exact figures to back up such a statement, that the web-building spider in Skylab turned less frequently than under pre-flight conditions while it constructed the sticky spiral.

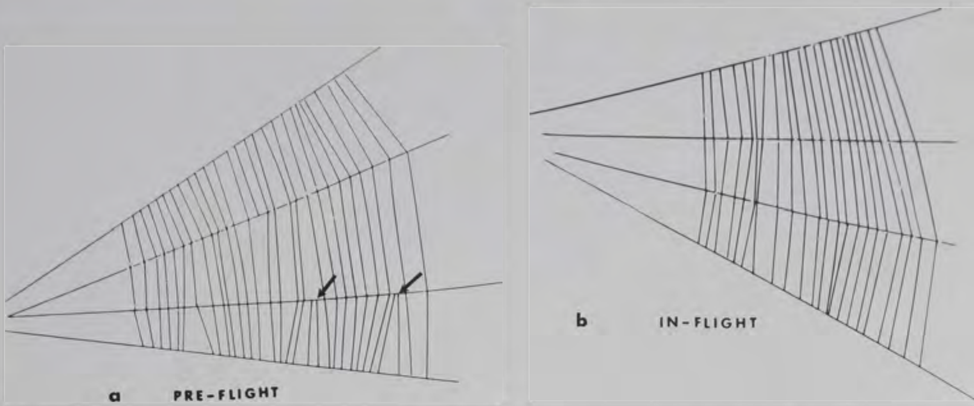

Fig. 2.–A low-contrast photograph of the highly regular web built in Skylab was overlaid with transparent paper and three sections in the East of the web traced with black tape (b); the same procedure was used for a pre-flight web (a), so that both figures could be compared. Note the absence of turning points (arrow) in the traced part of the spiral in the in-flight web (however, there were a few turning points in other parts of the web), the regularity of spiral spacing, and the seventh spiral turn from the center, which crosses two radii without being attached, something which has been described in d-amphetamine webs by Jackson (1974).

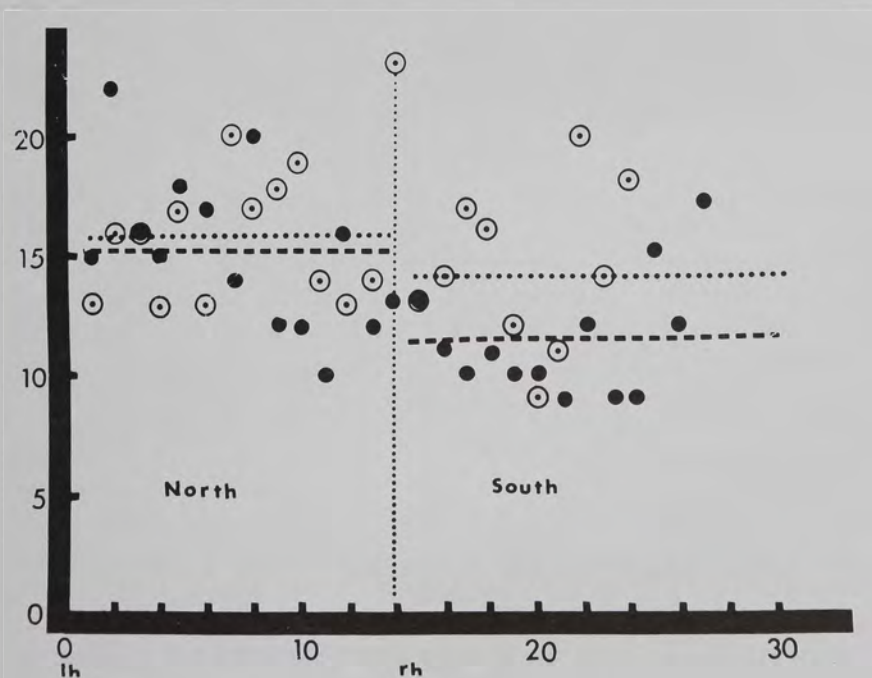

Fig. 3.–Radial angle size (ordinate) is plotted against number of radius (abscissa) for one pre-flight (single values: black circles; mean: dashed line) and the regular in-flight web (single values: open circles; mean: dotted lines). After South had been determined by the spider's head-down position, left horizontal is designated as one; right horizontal (rh) (=West) in both webs angle No. 14. Note the relatively large difference in mean values between North and South in the pre-flight web as compared to the in-flight web value, likely reflecting the absence of the gravity cue in Skylab.

Fig. 4.–This is one of several pictures of part of a highly irregular in-flight web. Similar patterns are built on earth directly before and after a spider's molting, by old spiders shortly before death, and after a high dose of a stimulant drug like dextro-amphetamine. We can not be sure that weightlessness caused this unusual pattern. Compare to Fig. 2 which indicates that under in-flight circumstances a regular web could also be constructed.

Unfortunately we were unable to measure shape and size of webs in flight; this would have required a camera with a wide-angle lense, or more distance between camera and web than was possible. However, there are close-up photographs of threads spun before and during flight. Evaluation of diameter suffers from uncertainty about which threads are photographed. If we assume that we measured on the pictures comparable threads in- and pre-flight–i.e., radii or draglines–the Skylab spiders laid some 20% thinner threads than the same animals on earth. Such a result is particularly interesting when one compares it to thread thickness measurements by Christiansen *et al.* (1962), performed on spiders which carried extra weight. Under that condition, which may be considered opposite to the weightless spiders in Skylab, thread thickness was found increased over lighter controls.

Screening of the television pictures shed some light on the time course at which the Skylab spiders adapted to the new and unusual conditions. On 28 August 1973 the CBS Evening News showed how one of the spiders, apparently the one which had been released on 4 August, was captured by the astronauts to be returned to its vial, and the other spider was released into the frame. An observer described this as "... the spider newly put in tumbled, its movements were head over heels, as never seen before; the animal rotated in space while moving in one direction, bounced off the frame and moved back. In contrast, the first spider ran very competently along the strands to escape from the astronauts." This observation would tend to confirm conclusions drawn from web records that there is a transition time during which spiders gradually acquire the skill to move "competently" under weightless conditions.

DISCUSSION

After it has been established that spiders are able to build orb webs in outer space, the most interesting question to be answered is whether these webs show changes characteristic for the special condition, and to interpret such changes. When all possible factors which could influence web-building are subtracted, can we find something which informs about the special way in which highly patterned behavior adapts to conditions which cannot have occurred before in the entire evolutionary history of the orb-web building spiders. One difficulty is the small sample size which prohibits statistical comparison. But a number of questions can be answered, from careful analysis of even an incomplete photograph of a web built in outer space.

Earlier experiments, particularly with high doses of drugs which cause paralysis or convulsions (Witt, 1971), have shown that web-building is a high priority activity of spiders; no food without webs and no webs without food (Peakall, 1968) and consequently no survival for the individual. The high priority of web-building apparently drove our animals to try repeatedly without success, until three days after opening of the transport vial the first animal was reported to build a web in August. There exist photographs and a protocol which indicate that the first web was preceded by considerable thread laying along the confining frame. As far as the photograph permits to see details, the first web looks like a medium-sized earth web of average regularity. It is not possible to reconstruct from the protocol whether this first web was destroyed by the astronauts or eaten by the spider, as is routinely done in our laboratory. We only know that the highly regular web, part of which is shown in Fig. 2, was built several days later, probably a week after release. Webs thereafter became irregular (see Fig. 4), and the spider was dead on return to earth after 59 days. The second spider built at least one large web which was not photographed, but reported as containing 22 radii and 30 spiral turns. This corresponds to a large web on earth (see Fig. 1). Later webs were highly irregular, but with the main characteristics of the orb, i.e. hub, radii, spiral and frame. It appears safe to conclude from such data that the spider can sufficiently reorient itself at zero gravity, to construct an orb web, gravity being a less important cue in web-building than had been assumed. The existence of horizontal orb webs suggests a similar interpretation, because there exist obviously different adaptations to gravity.

In order to get into Skylab and during their stay, the two animals were subjected to many stressful conditions which could have influenced web-construction. The pre-flight simulation experiments indicate that vibration and the special atmosphere had no measurable short-term effect on web geometry. Confinement in tubes similar to those used for transport to Skylab is known to cause relatively small and irregular webs (Reed, *et al.*, 1970); but it has also been shown that such effects wear off in three days. Only the first web of spider 1 and the irregularities in spider 2's web can possibly have been influenced by consequences of confinement in tubes.

Spiders can survive two to three weeks of food deprivation without apparent damage to web-building (Witt, 1963); however, they need frequent supply of water. It is known that one fly was put into each vial on 25 July, and that on 9 and 24 August "fillet" was put into the spiders' web; this was "kicked out," as we might have expected on the basis of its properties, which are strange to spiders. However, tests made at Marshall Space Flight Center had indicated that juices were extracted from pieces of rare fillet placed in the web. After the juices had been removed, the spiders would then eject the shrunken residue from the web just as they do a fly carcass. Photographic evidence was obtained which led to the decision to try to feed the space spiders with the astronauts' meat scraps. Spider 1 was at least watered once, on 11 August. Spider 1 was found dead on return to earth, spider 2 died on 16 September in space. The comparison of photographs and weights pre- and post-flight make it likely, that thirst and starvation at least contributed to their death. Spider 1 had changed from 180 mg before to 103 mg after the flight, spider 2 from 210 mg before flight to 50 mg at time of death. There is no indication that molting, which is always dangerous and which would likely have been very difficult in zero gravity, contributed to the spiders' death. Taking all data into consideration it is concluded that there were two quite healthy spiders in Skylab in the first two weeks, which afterwards changed into slowly dying animals. The decline in vigor could well explain increasing irregularity and decreasing size of webs. But the existing data do not permit us to say whether the animals' decline was due to specific Skylab stress conditions, starvation, or other circumstances. The time was too short and the animals too young to consider high age as a contributing factor.

Evaluation of web-patterns should shed some light on a problem which has puzzled investigators for some time (Mayer, 1953), and which had been given as one reason for taking web-building spiders into Skylab because it could not be solved on earth: is the North/South asymmetry of the orb-web dependent on the spiders' perception of gravity? One possibility could well be imagined, namely that a young spider is guided by gravity to produce shorter radii and wider radial angles on top of the web, and longer radii more narrowly spaced on the bottom. Older spiders had become so accustomed to the asymmetry, that they would retain the pattern without the cue. Our analysis (Fig. 3) indicates that even an adult animal which has presumably constructed about 100 asymmetric orbs in its life-time, shows a lack of North/South asymmetry in Skylab; this is independent of where we assume North to be. Decrease of pendulum turns, which help to fill a long frame with as much round spiral as possible, is another indication of pattern change in zero gravity. Another characteristic of many earth webs, namely an asymmetry of the position of the hub toward the corner of the frame, can be recognized in some of the space photographs. Mayer (1953) found an asymmetric (East/West) hub and a round spiral in a web built on a slowly rotating Klinostat. This appears not surprising for in-flight construction if the difficult circumstances are considered under which a thread is spun in zero gravity: the spider prefers the web close to the corner of the cage where it can stretch relatively short frame threads. The conclusion is that each web, including those built in outer space, reflects in its pattern also cues from the environment which were present during its particular construction.

Experiments conducted earlier had led to the tentative conclusion, that spiders can adapt thread thickness to body weight (Christiansen, *et al.*, 1962). It has been hypothesized that a heavier animal would require a thicker thread to hold it suspended. Comparison of web weights and thread lengths (length over weight used as an index of thickness) in animals before and after a lead weight has been fastened to the dorsum of the cephalothorax supported the hypothesis. The Skylab pictures which indicate that weightless spiders built most likely 20% thinner threads than the same animals pre-flight, point to the same mechanism. Some control mechanism which regulates silk thickness at the spinnerets of the weightless spider had possibly received signals through the central nervous system from the gravity perceptors that thinner silk would suffice. However, so little of the organs and the pathways possibly involved are known, that this remains merely a working hypothesis.

Fig. 5.–A female *Araneus diadematus* spider was photographed while it descended on its thread. Note the emergence of silk from the spinneret at the end of the spider's abdomen, and the position of one of the hind legs on the thread. However, spiders can also descend on a new silk strand without the help of a leg, using some mechanism along the path of the emerging thread to regulate speed; the animal's weight provides the pull.

Something that has been observed by nearly everybody in spiders is their ability to let out thread as they descend (Fig. 5), and that they can climb back up on such a thread, taking the silk in during the return. This observation, taken together with the fact that spiders always run on the underside of a web or a bridge thread, hanging down as they move, makes one aware of the important role which the use of the animal's own weight plays in locomotion and silk production. It is probably the absence of body weight which disturbed each of the two animals severely during the first days after release from the vial. They had to build frame threads by running along the given structures rather than dropping down; reports about their restless behavior preceding construction of the first web in Skylab can be interpreted as exploring such alternate mechanisms. Once the spiders had accomplished this, they showed no more difficulty in laying radii and spiral turns, with the result of accomplishing a large, regular web. Thus those features which underly detailed symmetry and make the orb an orb do not require gravity as a cue. The ability of an invertebrate animal with as rigid a behavior pattern as orb-web construction which is relatively independent of experience (Reed, *et al.*, 1970) to find alternate ways to complete a perfect trap for food and thereby increase its chance for survival, is possibly the most interesting finding in the evaluation of Skylab web records.

SUMMARY

Two spiders built orb-webs in Skylab under zero gravity only four days after release from transportation vials. The first webs resembled pre-flight controls in size and regularity, but the unusual distribution of radial angles and thinness of thread together with a probably low number of turning points in the spiral indicated a deviation from earth webs which can be attributed to the absence of gravity as a cue. Other web changes like a gradual decrease in regularity, diminished web size, and the spiders' decrease in body weight are identified as being likely consequences of starvation, Skylab stress and unknown circumstances not directly connected with zero gravity.

ACKNOWLEDGEMENTS

All records came from the NASA Marshall Space Flight Center. We acknowledge the help from Mr. Henry Floyd, manager of the Skylab Student Project, who provided the photographs and other data as the basis for our evaluation. Mr. Wolfgang Brandner from Marshall Space Flight Center participated in the early stages of experimentation and contributed substantially to the preparation of the Skylab Spider Experiment.

The web measuring work was carried out in the laboratories of the North Carolina Department of Mental Health, Research Section, and was supported by National Science Foundation Grant Number GB 25274 to Peter N. Witt. Thread measurements were performed at Cornell University.

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