THE ISRAELI ARTIFICIAL RAINFALL STIMULATION EXPERIMENT. STATISTICAL EVALUATION FOR THE PERIOD 1961–65

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1. Introduction

A rainfall stimulation experiment is being carried out in Israel by silver iodide seeding from an aircraft in a randomized crossover design. The operations are directed by Electrical and Mechanical Services (Mekorot, Ltd.), Mr. M. Cohen, Director, and are financed by the Israeli Ministry of Agriculture. The experiment is conducted under the guidance of the Rainfall Committee whose chairman is Professor E. D. Bergmann, and the related research work is performed at the Hebrew University, under the direction of Professor J. Neumann. The author is responsible for the statistical design and evaluation. Daily rainfall data are provided by the Israeli Meteorological Service from its regular network of raingage stations.

The present statistical design of the experiment [9] was adopted when an earlier design based on weekly units [8] was abandoned after a few weeks because those units were considered unsuitable for detailed analysis.

Earlier analyses excluded a small number of days, twelve, on which the aircraft could not be operated. Since the decision to ground the aircraft was not independent of atmospheric conditions, this exclusion might have introduced a slight bias. Therefore, the present analysis includes these few days and the results differ very slightly from those published earlier [10], [11], [12].

The experiment is based on comparison of amounts of precipitation in two areas of Israel: the North, and the Center, as shown in figure 1. These are separated by a buffer zone to avoid contamination of the atmosphere in one area when the other is being seeded. (The southern, more arid, part of Israel has been excluded from the experiment because its rainfall regime is different.) The interarea comparison reduces day to day variability of observations on precipitation, as rainfall in the two areas is highly correlated. The correlation between daily amounts of precipitation in the two areas was found to be $r = 0.81$, when means of eight stations were taken in each area and a square root transformation used to reduce heteroscedasticity and nonnormality. The amount of precipitation in each area is estimated by a simple average of daily precipitation re-

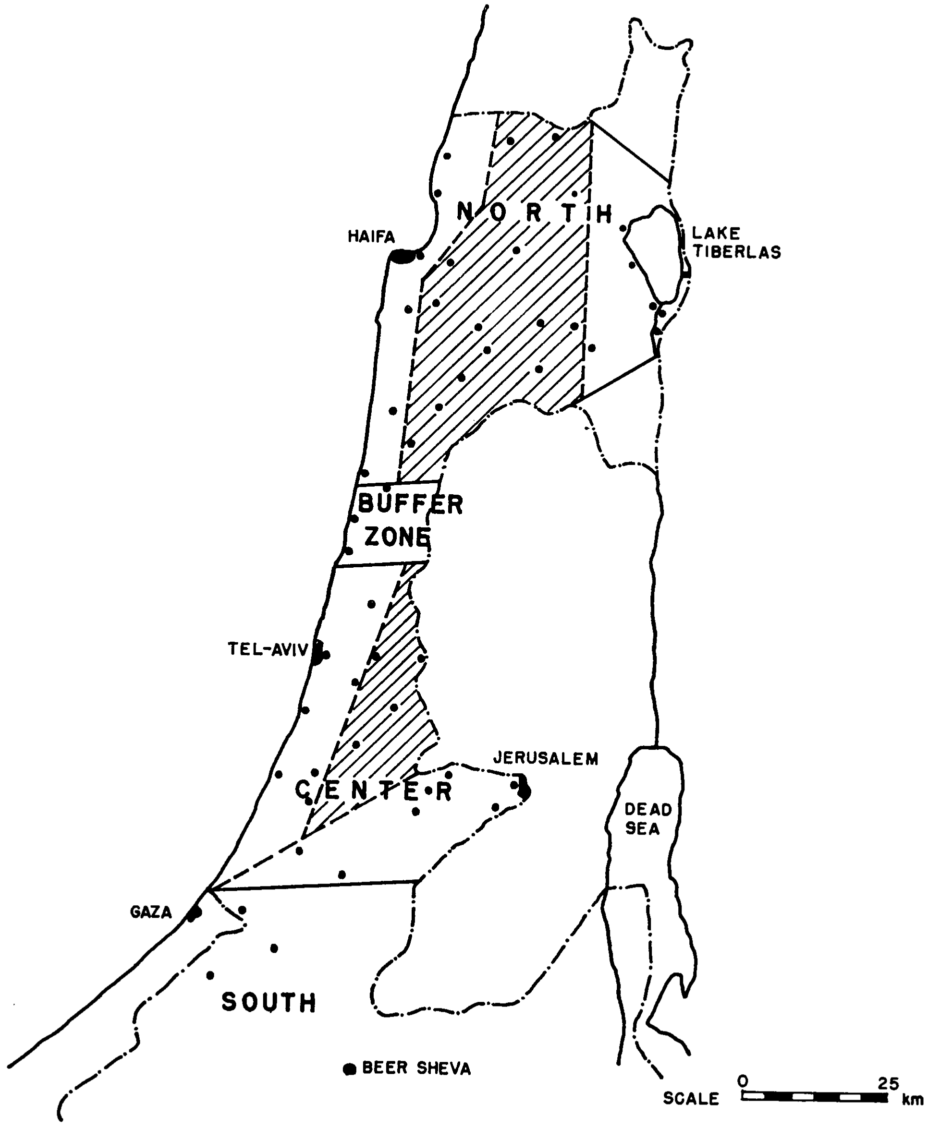

FIGURE 1

Map of Israel showing both experimental areas and the interior areas (shaded). Dots indicate raingages used in analysis as of 1964–65.

corded at different stations of the area. This method was considered to be simple and objective, and in view of high between station correlations it is probably as accurate as the intricate weighting procedure employed in Australia [1]. These amounts will be denoted N and C for the North and Center, respectively, with subscripts n and c indicating the area which was designated to be seeded, for example, N_c would be the amount in the North on a Center seeded day. The experimental variable is defined as $N - C$, the difference between the two area averages.

In some studies (see, for example, [25]) a ratio was used instead of a difference, so that periods with different amounts of precipitation received the same weights. Use of differences, on the other hand, ensures that an increase on a very rainy day be weighted more heavily than one on a day with little rain. It is not really known which method is more sensitive to potential seeding effects (see sections 3 and 5 below). One would suspect that the use of ratios might greatly increase variability and hence reduce the efficiency of the experiment.

Each experimental unit—24 hours—is designated ahead of time, that is, before the season starts, to be seeded in one or the other of the two areas. This designation is random and independent from day to day so that about one half of the days are designated to be North seeded and the rest to be Center seeded. Random designation permits probabilistic evaluation, that is, testing for statistical significance of the differences between the two sets of days. The results of the experiment are evaluated by comparing North seeded days with Center seeded days, using the difference $N - C$ as the comparison variable.

Such a crossover design with a double comparison of days and areas was first proposed by Adderley and used in Australia. It was used also in Canada [16]. Its statistical properties were discussed by Moran [20].

The advantages of this crossover design are readily demonstrated under the simplifying assumptions of normal distribution and equal variances of precipitation in both areas. Let r denote the correlation between N and C. A crossover experiment requires only $(1 - r)/2$ of the number of observations (days) needed by a single area design. Also, a crossover design requires only $1/2(1 + r)$ of the number of observations needed if a control area is added with a view to predicting target rainfall from it. With $r = 0.81$ as in Israel, these proportions are 8.5 per cent and 27.6 per cent, showing that much shorter periods of experimentation are required with the crossover design. It should be noted that even in the absence of correlation the crossover design still reduces the length of an experiment by one half.

Recent remarks by Bowen [4], [5] have raised the fear that these designs may be inefficient because the effect of silver iodide seeding may persist beyond the seeded day (or other experimental unit). Nominally unseeded days might show residual effects of earlier seeding, and the difference between seeded and unseeded days might be less than the real effect of seeding. All designs with short experimental units would therefore underestimate the true increase in rainfall due to seeding. Correct estimates could be obtained only from experiments with sufficiently long intervals between units, which would ensure that the effects of silver iodide seeding in one unit could not carry over to the next unit.

As of now, there is no compelling evidence that such persistence exists, and we feel that the use of the present type of short unit design is justified. However, the possibility that persistence exists should be investigated carefully, and data from current experiments may be tested for the existence of such effects (see sections 2, 5.4, 5.5).

Seeding techniques and equipment are similar to those used by the CSIRO group in Australia. Silver iodide is seeded in acetone solution by means of double burners fixed under the wing of a DC-3 plane. The solution is burned at the rate of 13 liters per hour, which corresponds to vaporization of 800 to 900 grams of AgI. The aircraft takes off whenever cloud conditions appear favorable, but seeding is carried out only after the cloud seeding officer has ascertained that cloud tops reach or exceed the $-5°$ C level. The extent of seeding in each season is shown [24] in table I. Seeding takes place just below cloud bases in an area displaced upwind from the target by half the wind speed per hour, according to the prevailing direction and speed of the wind.

TABLE I

SEEDING: NUMBER OF FLIGHTS, DAYS AND HOURS

	1961	1961–62	1962–63	1963–64	1964–65
Number of seeded days	20	34	36	39	43
Number of seeding flights	26	61	63	65	70
Hours of seeding	91	117	130	179	172

The experiment runs throughout the rainy season and includes each day as North seeded or Center seeded, according to the random designation and irrespective of whether seeding is actually carried out (see table II). It would be advantageous to restrict the evaluation of the experiment to those days on which seeding is feasible and to exclude the large number of days without rain clouds which cannot add to the sensitivity of the experiment. However, this is not permissible. Since seeding is attempted only when suitable clouds appear in the area designated to be seeded, the choice of days for seeding is biased in favor

TABLE II

UNITS EMPLOYED IN THE EXPERIMENT

Season	Date	Period	Unit of Time
1961 half	19. 2.61–15. 4.61 15.10.61– 5.11.61	weekly	0800 to 0800 hrs
1961–62	7.11.61–15. 4.62	daily	2000 to 2000 hrs
1962–63	16.10.62–15. 4.63	daily	2000 to 2000 hrs
1963–64a	1.11.63– 8. 1.64	daily	2000 to 2000 hrs
1963–64b	9. 1.64–30. 4.64	daily	0800 to 0800 hrs
1964–65	16.10.64–15. 4.65	daily	0800 to 0800 hrs

of days with good rainfall conditions in the designated area. The present evaluation relates, strictly speaking, to the designation to be seeded, rather than to actual seeding.

2. Overall evaluation

The main object of the experiment is to examine the possibility of stimulating rainfall by cloud seeding, and the secondary object is to identify conditions favorable or unfavorable to such stimulation. Various meteorological measurements and observations are being made. The importance of such measurements has often been stressed [22]. It is hoped to obtain interesting detailed analyses by classifying days according to synoptic conditions. The present statistical evaluation includes some first attempts at such analyses.

Detailed analyses of counts of freezing nuclei and other observations taken from the seeding aircraft and on the ground have been published separately [15].

Overall results in terms of average daily precipitation for each season and all seasons together are given in table III. Results for each area are presented separately for days designated to be seeded in the North and for days designated to be seeded in the Center. Beside the mean daily precipitation figures, the table shows the S/NS ratio, defined as the ratio of mean amounts $\bar{N}_n$ to $\bar{N}_c$ in the North and $\bar{C}_c$ to $\bar{C}_n$ in the Center.

TABLE III

MEAN DAILY PRECIPITATION (mm) PER STATION OF EACH AREA, IN SEEDED AND UNSEEDED AREAS WITH S/NS RATIO

Seeded means all days designated to be seeded, whether actually seeded or not. Unseeded refers to all unseeded days. Note the slight difference between this table and all the following tables from which "dry" days are excluded.

Station	North			Center			
Designation	Precipitation North Seeded $\bar{N}_n$	Precipitation Center Seeded $\bar{N}_c$	Ratio S/NS $\bar{N}_n/\bar{N}_c$	Precipitation North Seeded $\bar{C}_n$	Precipitation Center Seeded $\bar{C}_c$	Ratio S/NS $\bar{C}_c/\bar{C}_n$	Average Ratio S/NS
Total	3.232	3.038	1.064	2.351	2.934	1.248	1.152
1961	2.495	0.744	3.353	1.050	0.853	0.812	1.650
1961–62	3.209	4.350	0.738	1.827	3.391	1.856	1.170
1962–63	2.044	2.911	0.702	1.157	1.991	1.722	1.099
1963–64a	2.957	2.471	1.197	3.991	3.417	0.856	1.012
1963–64b	4.318	3.254	1.327	2.406	3.393	1.410	1.368
1964–65	4.262	3.185	1.338	4.010	3.882	0.968	1.138

As designation of seeded area was random, the days of both kinds should have had similar amounts of natural precipitation, except for random variability.

Thus the amounts N_n and C_n on days designated to be North seeded should have been similar to the amounts N_c and C_c, on days designated to be Center seeded. In the absence of random variability the S/NS (seeded/nonseeded) ratio of each area would have been equal to one if seeding had had no effect, whereas if seeding had been effective the S/NS ratio of each area would have exceeded one. In fact, neither of these explanations fits the results in table III which show that for each season, except 1963–64b, the S/NS ratios for the two areas deviated from one in opposite senses. In other words, $\overline{N}_n - \overline{N}_c$ has had the same sign as $\overline{C}_n - \overline{C}_c$. Apparently, in any one season, the random differences in country wide precipitation between North seeded days and Center seeded days were much larger than any possible seeding effect.

The results of table III must not be taken to indicate differential seeding effects in the two areas. They merely show that rainfall stimulation experiments based on randomized seeding in a single area are subject to enormous variability. To give any hope of revealing seeding effects, single area experiments must be continued for a large number of years.

For the initial design of the Santa Barbara experiment it was calculated that well over ten years of experimentation in one area are required to give over 75 per cent chance of finding a 5 per cent significant result if seeding increases precipitation by 20 per cent ([22], p. V-32). The Israeli experiment requires only four to five years for the same chance of finding a significant result [8]. Part of the difference may be due to different rainfall regimes, but most of it results from the advantages of the crossover design which allows interarea comparisons. The extent of this advantage has been discussed in section 1 above.

As the difficulties with single area experiments were foreseen, the Israeli experiment has been based from the outset on interarea comparisons by means of $N - C$ differences or N/C ratios. Random variability for such comparisons is considerably reduced, since most day to day variation affects N and C similarly, and thus does not affect either $N - C$ or N/C. Using these comparisons one may expect conclusive results with a relatively short experiment [20]. The product of the S/NS ratios for the North $\overline{N}_n/\overline{N}_c$ and for the Center $\overline{C}_c/\overline{C}_n$ gives the double ratio

$$\frac{\text{seeded amounts in N} \times \text{seeded amounts in C}}{\text{unseeded amounts in N} \times \text{unseeded amounts in C}} = \frac{\overline{N}_n\overline{C}_c}{\overline{N}_c\overline{C}_n}. \tag{2.1}$$

This can be rewritten $(\overline{N}_n/\overline{C}_n)(\overline{C}_c/\overline{N}_c)$ which shows that every day, whether North seeded or Center seeded, appears in the numerator as well as in the denominator, so that effects of random designation of the days are reduced. On the other hand, a positive seeding effect would increase both numerator factors without affecting the denominator, so that an average estimate of the proportionate effect of seeding can be obtained by the square root of this double ratio. (This is an unweighted geometric mean of the two area S/NS ratios.) These average S/NS ratios are presented in the last column of table III and show greater amounts of rainfall on seeded than on unseeded days. Such differences are found in varying degrees in all seasons, the average excess of precipitation under seeding being about 15 per cent.

At first it seemed that the highly positive results of the short first half season were followed by less and less positive results in later seasons. Similar effects have been observed in other experiments (at Delhi [23], [25], and in Australia [4]) and Bowen has tentatively suggested that this may be due to a "persistence" effect [4]. The results of the last two seasons, however, run counter to this "trend" which may be merely random year to year variation. (Indeed, season to season differences are found to be negligible. See section 5.4, below.)

An interesting speculation [18] is that experiments tend to be discontinued after a few years of apparently poor results. Experiments with "unsuccessful" results in the first season or two may often not be reported at all. As a result, the experiments whose results are published would be those with initial "successes" which are usually followed, sooner or later, by less "successful" seasons. This could account for the apparent downward "trend" among published experiments.

It would be interesting to try and trace all experiments which have been initiated and check if this "trend" might really be due merely to selection of initially "successful" experiments for publication.

3. Evaluation by single days and significance tests

Probabilistic evaluation of the results of the experiment must be done by single days rather than by the averages presented in the previous section, since the randomization is by days. The average S/NS ratio on days on which seeding actually took place, 1.241, was higher than on days without seeding, 0.752. We cannot tell how much of this difference was due to seeding and how much to selection of days with appreciable amounts of rainfall in the area allocated to seeding. It has already been mentioned that it is not possible to analyze only days which were actually seeded without risking bias. However, it is possible to exclude from the analysis most of the days without any rain at all, and it is obviously desirable to do so since most of these days have no rain clouds and therefore cannot add information on possible seeding effects. (A similar suggestion of analyzing rainfall increases in relation to the number of rainy days, or per rainy day rather than per average day, has been made recently by Lopez and Howell [19]. Accordingly, days are classified as "dry" and excluded from the analysis if there is no precipitation at all in the buffer zone. Precipitation in the buffer zone at stations near the sea was chosen for this classification, because it can hardly ever be affected by seeding operations in either area, and hence this classification is most unlikely to introduce bias.

Correlation of rainfall amounts, after square root transformation, in the buffer zone (three stations) and in either of the experimental areas is about $r = 0.75$. Therefore, the buffer "dry" days are mostly rainless or have very little rainfall in the experimental areas. This was checked on data on the experimental seasons.

Exclusion of dry days reduces the number of days by almost two thirds at the expense of ignoring a negligible percentage of precipitation in the experimental areas. See table IV.

TABLE IV

PERCENTAGE OF PRECIPITATION ON DAYS WITH RAIN IN BUFFER ZONE

	Number of Days	Total Precipitation in mm per Average Station North	Center
Rainy	281	2395.78	2040.86
Total	783	2456.00	2063.75
Percentage of rainy to total	35.9	97.5	98.9

The information that might be lost by excluding these days is obviously negligible. On the other hand, by excluding them one gains homogeneity in the days analyzed and reduces variability. Calculations have confirmed that exclusion of dry days increases the power of the analysis.

Daily data are best analyzed by nonparametric methods since the experimental variable $N - C$ does not follow any known probability law and is not readily normalized. Even for large samples, the common normal distribution methods, such as t tests, are only approximately valid because rainfall amounts on successive days are not independent. Correlation of rainfall amounts on successive days, calculated with the square root transformation, is $r = 0.55$. For North-Center differences the corresponding correlation is only $r = 0.14$ (see [14] also). Only nonparametric methods based on randomization in the design will give exact significance tests.

Each North seeded day is compared in table V with each Center seeded day, that is, each daily (N_n, C_n) pair of observations is compared with each (N_c, C_c) pair. Comparisons are counted as positive if the experimental variable is in the direction one would expect if seeding were effective, that is, if $(N_n - C_n)$ is greater than $(N_c - C_c)$. If seeding had no effect the probability of a positive comparison would clearly be one half. If the per cent of positive comparisons exceeds 50 per cent this is an indication of a possible effect of seeding. Its significance can be tested by the Wilcoxon-Mann-Whitney nonparametric procedure (see appendix). Details of these comparisons and tests are presented in table V.

The overall picture presented in table V shows a slight excess of positive comparisons beyond 50 per cent, with considerable year to year variation. For the entire experiment, 53 per cent of all comparisons of North seeded $(N_n - C_n)$ differences with Center seeded $(N_c - C_c)$ differences are positive, and the remaining 47 per cent are negative. Thus, there are only 6 per cent more comparisons in favor of seeding effects than in the contrary direction. The chance of a random result as much above 50 per cent as this is about 19 per cent, so that this outcome by itself might well be due to chance, that is, it is not significant.

TABLE V

COMPARISON OF NORTH SEEDED AND CENTER SEEDED DAYS BY SEASON PERCENTAGE OF POSITIVE COMPARISONS AND WILCOXON-MANN-WHITNEY TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

	Number of Days		Comparisons			
	North Seeded	Center Seeded	Total	Positive Per Cent	W-M-W Statistic	Significance Level
Total	147	134	19698	53.03	+0.878	0.190
1961	14	12	168	62.50	+1.080	0.140
1961-62	30	27	810	52.22	+0.288	0.387
1962-63	27	22	594	49.33	−0.080	0.532
1963-64a	11	9	99	46.46	−0.266	0.605
1963-64b	31	26	806	64.39	+1.858	0.032
1964-65	34	38	1292	47.99	−0.293	0.615
Pooled				53.63	+1.041	0.149
Between season variation				3.783	5 d.f.	0.581

A more sensitive analysis is obtained by relating the experimental variable to another, concomitant variable with which it is correlated, but which is not affected by the experiment. A suitable concomitant variable in the present experiment is the difference between amounts of precipitation in the buffer zone and in the South. Both these amounts are unaffected by seeding, but their difference is correlated with the North-Center precipitation difference, as might be expected by considering that both are North-South differences, the one being displaced a certain distance from the other. The correlation between the North-Center difference and the buffer-South difference is about $r = 0.50$ for daily rainfall.

It would seem that in the choice of two areas for concomitant variation (also see Bowen's suggestion on a similar choice [4]) it is more important to have them close to the corresponding experimental areas so as to achieve high correlation than to have them far away to avoid possible contamination. For, under the null hypothesis of no seeding effect there can also be no contamination. Hence tests would remain valid, and exact, and the only risk in using concomitant areas that are too close might be some reduction in power. However, unless contamination was very serious, this reduction of power would probably be more than offset by the gain in power due to higher correlation with the concomitant variable.

A simple way of using the buffer-South difference to increase the sensitivity of the analysis is by breaking down the data into groups of days with similar buffer-South differences, and making comparisons only between days of the same group. The days of each group are tested separately for significance, and the results of the separate tests are then pooled to give an overall test. This does not make as good use of the concomitant variable as a regression line adjustment would, but it requires no assumptions of linearity, and nonparametric methods can be used without the derivation of new statistics.

It is plausible that for large samples an adaptation of the Wilcoxon-Mann-Whitney test to data adjusted by regression on a concomitant variable is valid, but this has not yet been proved directly. However, such a use of a concomitant variable is known to be valid not only for normal tests but also for another class of nonparametric tests [3].

Separate analyses and tests are shown in table VI for each of ten groups,

TABLE VI

COMPARISON OF NORTH SEEDED AND CENTER SEEDED DAYS WITH BREAKDOWN BY BUFFER-SOUTH DIFFERENCE, AVERAGE S/NS RATIO, PERCENTAGE OF COMPARISONS POSITIVE WITH W-M-W TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

Buffer-South Difference	Average Ratio S/NS	Number of N Seeded Days	Number of C Seeded Days	Comparisons Total	Comparisons Positive Per Cent	Standardized W-M-W Statistic	Significance Level
$\geqq 20$,	1.148	7	14	98	60.20	+0.746	.228
$\geqq 10$, < 20	1.718	8	13	104	72.12	+1.666	.048
$\geqq 5$, < 10	1.354	15	14	210	71.90	+2.008	.022
$\geqq 3$, < 5	0.714	8	11	88	42.05	−0.578	.718
$\geqq 1$, < 3	0.915	25	12	300	40.67	−0.908	.818
$\geqq 0$, < 1	1.582	37	33	1221	45.58	−0.635	.737
$\geqq -1$, < 0	1.485	11	9	99	68.69	+1.406	.080
$\geqq -5$, < -1	1.402	11	12	132	68.18	+1.477	.070
$\geqq -10$, < -5	1.480	10	7	70	57.14	+0.488	.313
< -10	1.097	15	9	135	60.74	+0.865	.194
Total		147	134	Pooled Average	56.02	+1.684	.046
Between group variation					11.232	9 d.f.	.261

starting from the group of days on which buffer rainfall exceeded rainfall in the South by at least 20 mm and ending with the group of days on which buffer rainfall fell 10 mm short of southern rainfall. The separate results for the different groups will be considered later in section 5.6. For the present purpose, the different results are pooled by means of a weighted average of the percentages of positive comparisons, whose significance is tested (see appendix). On the average 56.02 per cent of comparisons are found positive (as compared to 53 per cent by the less sensitive method which does not take a concomitant variable into account; see table V) and this is slightly beyond the critical point for 5 per cent significance.

Adjustment for concomitant variation is a well known method of obtaining more sensitive analyses of experimental results ([6], chapter 4). It was considered from the outset that such a method of analysis, if available, would be preferable to the test of table V which uses unadjusted data. And indeed the results by this analysis indicate seeding effects more strongly (though that in itself must not be used as an argument for using this method in the present experiment). As a single overall significance statement regarding this experiment it would seem appropriate to state the result of this more sensitive analysis and say that the results are just significant at the 5 per cent level.

4. Evaluation in interior of areas

Additional analyses were restricted to the interior regions of the two experimental areas. (Similar restrictions to a "target" area within the seeded area are described in [27] and [28].) The proposal to limit the areas under analysis was justified operationally in terms of restricted possibilities of flying. It was claimed that the seeding plane generally did not fly outside visual contact with the coastline so that there could have been no seeding effect near the coast; hence a 10 km wide coastal strip must have been unaffected. It was also claimed that seeding by the coast could not have been effective as far inland as the Jordan valley. Finally, the southeastern part of the Center area, including Jerusalem, could not have been affected by seeding under the prevailing southwesterly winds, since flying was not carried out along the Egyptian occupied Gaza strip. Hence, all these zones were excluded from the analysis of this section.

Average S/NS ratios and comparisons of days are summarized in table VII for each season. It should be noted that restriction of areas to their interior zones severely reduced the number of stations available, especially in the Center (see table VIII). For 1961–62, 1962–63 and 1963–64a only stations with automatic recording raingages could be used, because of the unconventional definition of a day from 2000 to 2000 hours.

The analysis for the interior parts of the experimental areas as given in table VII indicates positive seeding effects more definitely than the analyses for the entire areas in tables III and V. Average S/NS ratios are higher for all seasons except 1961, and the percentage of positive comparisons is higher except for 1963–64a. For all seasons together a 23.5 per cent rainfall increase is indicated, compared to 15.2 per cent for the entire areas, and the percentage of positive comparison is 57 per cent compared to 53 per cent. These results for the interior parts are significant at the 5 per cent level. Analysis in groups defined by the buffer-South differences, similar to that of table VI, shows significance at an even lower level.

There may be some misgivings about this restriction as it was suggested only after results of the first two and a half seasons were available, with detailed figures for each station, showing higher S/NS ratios for the interior parts of the

TABLE VII

ANALYSIS OF RAINFALL IN INTERIOR PARTS OF AREAS BY SEASON AVERAGE S/NS RATIO AND PERCENTAGE OF COMPARISONS POSITIVE WITH WILCOXON-MANN-WHITNEY TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

	Number of Days	Average S/NS Ratio	Positive Comparisons Per Cent		Significance Level
Total	281	1.235	56.93		0.031
1961	26	1.544	64.29		0.109
1961–62	57	1.218	52.90		0.354
1962–63	49	1.340	59.43		0.130
1963–64a	20	1.082	39.39		0.788
1963–64b	57	1.519	65.69		0.021
1964–65	72	1.169	53.25		0.318
Pooled Average		—	56.83		0.070
Between season variation			4.073	5 d.f.	0.539

experimental areas. After all, by posterior selection of suitable subareas one could have "proved" almost anything one might have wished to prove. The fact that little seeding was done in particular regions might even have been due to lack of seeding opportunities in these regions, so that lack of rain could have reduced seeding in certain areas, rather than vice versa. However, for both parts of the 1963–64 season, and for the 1964–65 season as well, the same pattern was repeated, and average S/NS ratios were again higher for the interior parts than for the entire areas (compare table VII to table III). This supports the claim that the restriction is a valid one, and allays misgivings about the restricted analysis. And yet, one would feel more confident about using data for interior areas if this pattern were repeated in later seasons as well.

TABLE VIII

NUMBER OF STATIONS AVAILABLE

	1961	1961–62	1962–63	1963–64a	1963–64b	1964–65
North	27	19	30	25	27	27
(Interior)	(14)	(12)	(14)	(14)	(14)	(14)
Center	20	14	18	18	18	18
(Interior)	(6)	(6)	(4)	(4)	(4)	(4)

These results are more conclusive than those for the entire areas, but it is felt that, for the reasons indicated above, they should be treated with caution.

5. Some further analyses

There are many valid ways of analyzing the results of this, or any other experiment. Each method of analysis lays stress on some aspects of the experiment and ignores others. Since so little is known about the way seeding might affect precipitation it is very difficult to decide beforehand what method of analysis would be most appropriate. It is obviously not permissible to be guided by the results themselves in choosing an analysis stressing those features that are most evident in the data. Therefore, for the present experiment we have adhered to the decision made at the time of designing the experiment and used a nonparametric method of analyzing daily North-Center differences as described in section 3, above.

Even though the overall evaluation of the experiment must be made along lines decided on prior to a study of the results, this is not to say that other features, suggested by the data themselves, should be ignored. A number of additional analyses are presented in this section with a view to throwing light on issues that arose during the experiment and in the course of the present controversy about the effectiveness of cloud seeding. Strictly speaking, significance tests are applicable only to prior hypotheses, whereas for hypotheses suggested by the data they may be regarded merely as descriptive statistics without exact probabilistic meaning.

5.1. *Confidence bounds and median estimates.* The method of pairwise comparisons of North seeded days with Center seeded days and the Wilcoxon-Mann-Whitney significance test may also serve to give an alternative estimate of the percentage increase in precipitation amounts due to seeding, and provide confidence bounds for such an estimate. For this purpose it is necessary to make some simplifying assumption regarding the form of rainfall increase due to seeding. It was assumed that natural rainfall is always increased by a constant ratio in the area allocated to seeding. This is undoubtedly a much oversimplified assumption but could serve as a first approximation. Next to nothing is known about the form the rainfall increase may take. Some calculations regarding multiplicative and additive, constant, and random, increase are given by Bernier [2].

Denoting, then, the ratio of seeded to natural amounts by $1 + \delta$, so that δ denotes the proportionate increase, any numerical value of δ may be tested after correcting all seeded amounts of rain by dividing them by the ratio $1 + \delta$. If δ is the true proportionate increase, this division would reconstruct the "natural" amounts of rain.

Now, for natural rainfall the differences between North seeded days and Center seeded days are entirely random so that reconstructed "natural" amounts should not give 5 per cent (10 per cent) significant tests except once in 20 (10) times. If the test is not significant the reconstruction may be considered plausible and the value of δ acceptable. If it is significant, the value of δ is not acceptable. Hence, successive values of δ may be tried and those for which the test is not significant provide a confidence interval for δ ([17], p. 269). By the same reasoning the value of δ for which exactly one half of the comparisons are positive may be called a median estimate of δ.

Reconstruction of "natural" amounts of rainfall for various values of δ and testing significance by means of the Wilcoxon-Mann-Whitney test involve a large amount of computation. An iterative procedure was therefore programmed on an IBM 1620 computer [13] and successive values of δ tested until 90 per cent confidence bounds and a median estimate were determined with sufficient accuracy.

On running such an analysis for the data for all days, as in table V and without breakdown by a concomitant variable, the median estimate of the increase in precipitation is found to be +5.5 per cent, but the 90 per cent confidence interval for δ is very wide and ranges from −6.5 per cent to +19.0 per cent. The fact that the null hypothesis of no seeding effect is not rejected significantly by this method (table V) is here expressed by a negative lower bound for the confidence interval, which is another way of indicating that the evidence of that table does not allow confident assertion of a positive seeding effect.

These calculations should be considered illustrative, and their results not be taken too literally because it is most doubtful whether cloud seeding always results in a fixed proportionate increase in rainfall. In fact, evidence is presented in the following section that cloud seeding effects may vary a good deal from day to day, so that the results of this section merely serve as a rough average approximation.

5.2. *Variations in effectiveness of cloud seeding.* The difference between the results of the daily data analysis of sections 3 and 5.1 and the analysis of rainfall totals in section 2 is striking. As compared to the table III estimate of 15.2 per cent increase in rainfall, the median estimate is only 5.5 per cent. Again, the mere 53 per cent of positive comparisons recorded in table V does not accord well with the sizable increase in table III.

Greater apparent effects are suggested by the method of comparing rainfall totals for each season or for the entire experiment (table III) than by the method which makes North-Center comparisons separately for each day (table V and section 5.1). Apparently, the observations are such as to affect totals more than day to day comparisons. Now, comparisons merely count *whether* the North-Center difference is greater on the North seeded day than on the Center seeded day, but do not record *how large* this difference is. Totals, on the other hand, are affected by size as well as sign of differences. Thus, if there were a few days with very large apparent seeding effects, they would be too few to add appreciably to the count of positive comparisons, but they might be large enough to increase the totals noticeably. This might explain the observed difference between the results of the two calculations.

Daily North-Center precipitation differences for each season are plotted in figure 2 from which it is indeed evident that in several seasons a very few days have extremely large differences in the direction expected if seeding were effective. A striking case is the 1964–65 season in which three days have very large differences in the direction expected from seeding, but most other days show no noticeable pattern. For that season the totals comparison (table III) indicates a clear excess of rainfall with seeding (13.8 per cent), whereas the day to day comparisons indicate the contrary; only 48 per cent of comparisons are positive (table V).

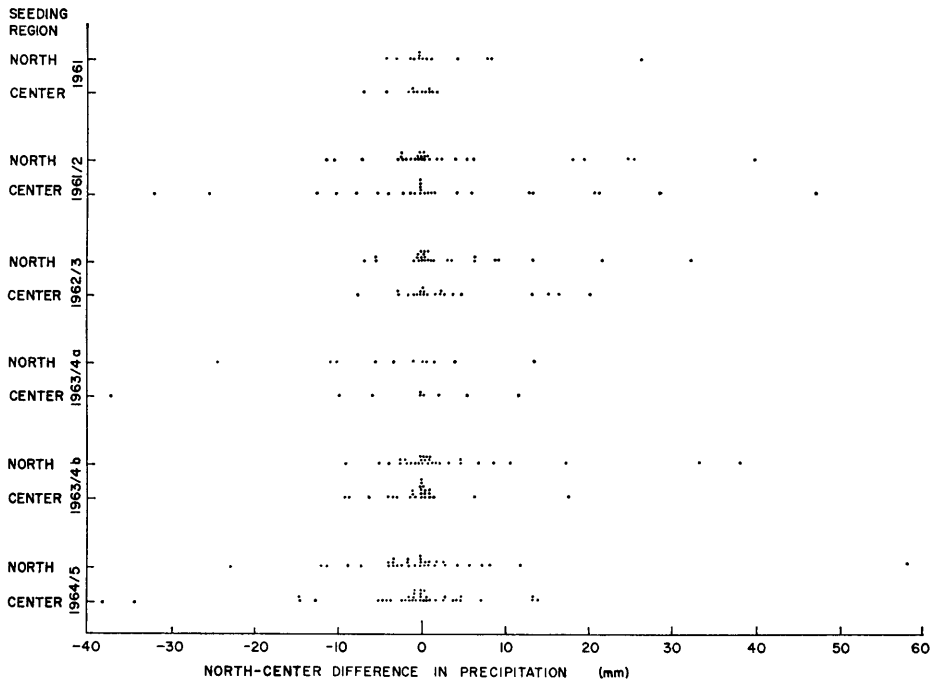

FIGURE 2

Plot of daily North-Center difference in precipitation, per season and seeding region.

If this is not a random effect (a matter which it is difficult to determine since the number of days on which such large effects have been noticed is very small), it raises interesting speculations about the possible effect of cloud seeding. Could it be that the effect of seeding is negligible on most days, but is very considerable on some particular days? It would be most helpful if one could identify some synoptic peculiarities of the few days concerned, and research should continue in this direction. Schleusener [26] has pointed out that similar observations have been made in the Mexican experiment. Pérez Siliceo *et al.* [27] write ". . . suggests that seeding is not always effective but that, whenever the right meteorological conditions occur, it is highly efficient . . . ," and ". . . increases in the rainfall at the target area are due to a relatively small number of cases in which seeding is effective."

5.3. *Normal tests.* It is usually convenient to use the statistical techniques that have been derived for normally distributed variables. The present variable, however, is markedly nonnormal (see figure 3) with an excess of values near zero

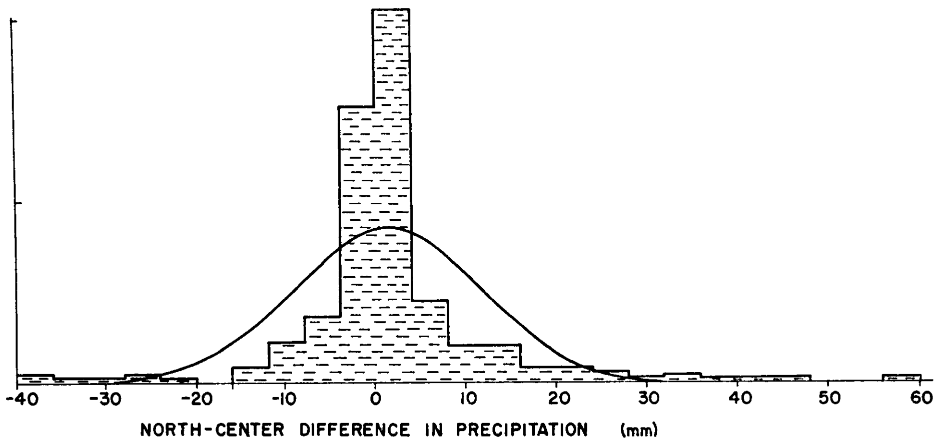

FIGURE 3

North-Center difference in daily amounts (mm) of precipitation. Histogram of observed distribution and normal curve with same mean and variance.

and of very large deviations, both positive and negative. Moreover, there is a slight dependence between the values for successive days (see section 3). Hence, tests based on normal theory are at best approximate.

Normal theory methods use means and hence are more sensitive to individual large observations than are ranking methods such as the Wilcoxon-Mann-Whitney test of section 3. Indeed, the normal test calculated for the entire experiment reaches the critical point for 5 per cent significance even without breakdown or adjustment for a concomitant variable.

A slightly better approximation to normality could be obtained by using the difference between the square roots of North and Center precipitation figures [8].

5.4. *Season to season differences.* It might be that real effects within each season of experimentation were swamped by analyzing the days of all seasons together. This could happen if season to season variation were appreciably larger than day to day variation within each season. Means and variances for each season are shown in table IX along with the corresponding analysis of variance. The F ratios are very close to one, so that there is no evidence of extra season to season variation, and no indication that the days of all seasons should not be analyzed together.

To test whether seeding effects might have been the same in all seasons, the variance of percentages of positive comparisons in different seasons is computed and checked against the chi square distribution with $(k - 1)$ degrees of freedom,

TABLE IX

DATA ON NORTH-CENTER DIFFERENCES FOR EACH SEASON

Table excludes six rainy days on which the plane was not operational.

	North Seeded Days			Center Seeded Days		
	Days	Mean	Variance	Days	Mean	Variance
Total	143	2.229	105.781	132	0.210	107.472
1961	14	3.061	60.634	12	−0.669	6.462
1961–62	30	3.707	125.826	27	2.283	243.197
1962–63	26	3.186	74.077	22	3.241	48.968
1963–64a	10	−2.408	100.396	9	−3.666	195.935
1963–65b	30	3.137	94.474	24	−0.065	24.317
1964–65	33	0.358	144.823	38	−1.651	106.312
	d.f.	Sum of Squares	Mean Square	d.f.	Sum of Squares	Mean Square
Between years	5	454.135	90.827	5	595.985	119.197
Within years	137	14566.767	106.327	126	13482.847	107.007
F ratio			0.854			1.114

where k is the number of seasons compared (see appendix). The variance, as noted at the bottom of table V, is far from significant, so that there is no evidence that seeding effects have not been the same in all seasons.

The homogeneity of seasons as regards rainfall amounts and seeding effects is also evident from the fact that the percentage of positive comparisons and the significance levels as estimated from all days together—first line of table V—and as obtained by pooling the seasons—bottom of table V—do not differ much. Clearly, there is no point in keeping the seasons apart in this analysis.

5.5. *Monthly differences.* Analyses of the data taking each month separately are of interest for two reasons. First, there might be meteorological differences resulting in different effectiveness of seeding in different months. Second, if Bowen's [5] suggestion of persistence of seeding effects is true, any possible seeding effects in later months would be obscured by contamination, and seeding effects should show most clearly in the earlier months of each season.

Data for each month are presented in table X, merging the same months of different years. Some differences between months appear but are not significant, the probability of random variation as large as this being 17 per cent. If anything, the effects of seeding would seem most evident in March and April, contrary to what one would expect if persistence existed.

Indeed, neither the season to season variations nor the within season variations of the results of this experiment lend support to Bowen's persistence hypothesis.

5.6. *Differences according to amounts of natural rainfall.* The effect of seeding is unlikely to be the same under all conditions. A variety of synoptic factors probably has a role in furthering or inhibiting the artificial stimulation of

TABLE X

ANALYSIS BY MONTH
AVERAGE S/NS RATIO AND PERCENTAGE OF COMPARISONS POSITIVE WITH WILCOXON-MANN-WHITNEY TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

Month	Number of Days	Average S/NS Ratio	Positive Comparisons Per Cent		Significance Level
Oct.–Nov.	34	1.176	51.43		0.444
Dec.	50	1.093	46.56		0.662
Jan.	67	1.145	61.57		0.053
Feb.	62	1.021	45.41		0.730
Mar.–Apr.	68	1.663	66.83		0.009
Pooled average			55.35		0.064
Between month variation			6.366	4 d.f.	0.174

precipitation. Analyses by prevailing types of clouds, their water content, presence of natural freezing nuclei, and so forth, might indicate which factors make seeding effective. However, in the present experiment it took a certain time until the collection of data on relevant variables was systematized; hitherto few measurements have been available for a period long enough to warrant being included in this statistical analysis.

A rough idea of differential seeding effects according to amounts of natural rainfall could be obtained by classifying days according to the amounts of precipitation in the buffer zone, and testing for seeding effects separately in each class. Such an analysis is presented in table XI for all seasons together, and seems of interest in view of suggestions that seeding has different effects under conditions of heavy precipitation than under conditions of little or no natural precipitation.

Positive seeding effects appear for all amounts of natural rainfall (as measured in the buffer zone) except the relatively small group of days with 2.51 to 5.00 mm of rain. Again, in all groups except that one, more than 50 per cent of the comparisons are positive. However, the test of differences between groups is not significant even at the 20 per cent level, so that these differences may well be due to chance.

5.7. *Differences according to the concomitant variable.* The breakdown according to the difference between rainfall in the buffer zone and the South was used above (section 3) for a more sensitive pooled test of the whole experiment. In addition to this we may consider the individual rows of table VI and see if seeding may have been differentially effective in different groups.

The test for differences between groups is far from significant, so that one would tend to conclude that there is no difference in effectiveness of seeding in

TABLE XI

ANALYSIS ACCORDING TO PRECIPITATION IN BUFFER ZONE
AVERAGE S/NS RATIO AND PERCENTAGE OF POSITIVE COMPARISONS
WITH WILCOXON-MANN-WHITNEY TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

Precipitation in Buffer Zone	Number of Days	Average S/NS Ratio	Positive Comparisons Per Cent	Significance Levels
None	502	0.970	—	—
Some	281	1.155	53.03	0.190
Up to 1 mm	88	1.376	51.33	0.415
1.01–2.50 mm	42	1.142	61.10	0.123
2.51–5.00 mm	37	0.925	37.94	0.894
5.01–12.50 mm	56	1.327	66.03	0.020
Over 12.50 mm	58	1.145	54.04	0.303
Pooled			54.43	0.105
Between group variation		5.863	4 d.f.	0.210

different groups. However, the rows of table VI form a pattern which cannot be ignored (but to which the test of significance is not sensitive). Positive seeding effects appear in all groups *except* those with a small positive buffer-South difference. But this is the most frequent size of difference. If this pattern is not random, seeding is more effective when buffer-South differences are unusually large or small, that is, either very large or negative. Could it be that when rainfall conditions deviate from the mode in the sense of an unusual distribution over different parts of the country, there is some atmospheric instability which furthers seeding effectiveness?

5.8. *Differences according to cloud temperatures.* An interesting additional breakdown would be according to cloud top temperatures which are supposed to be a crucial factor in determining silver iodide seeding effectiveness. However, cloud levels are difficult to measure precisely and vary a good deal within any one day. Hence, the present analysis is limited to temperatures at the 700 mb altitude, as recorded by a radiosonde, in the hope that this may give some indication of cloud temperature effect.

The data are presented in table XII with days grouped by single degrees centigrade. It is not easy to interpret this table. The S/NS ratios jump around pretty erratically and the percentages of positive comparisons do not vary at all significantly. And yet, the largest ratios and the most nearly significant percentages are almost all at temperatures $-5°$ C, $-6°$ C and perhaps also $-4°$ C and $-7°$ C. Could this be merely a chance pattern?

TABLE XII

ANALYSIS ACCORDING TO TEMPERATURES AT 700 mb ALTITUDE
AVERAGE S/NS RATIO AND PERCENTAGE OF POSITIVE COMPARISONS
WITH WILCOXON-MANN-WHITNEY TEST OF SIGNIFICANCE

"Dry" days have been excluded. Positive means that $N - C$ rainfall difference is greater on the N seeded day than on the C seeded day.

Temperature (centigrade)	Number of Days	Average S/NS Ratio	Positive Comparisons Per Cent	Significance Level
up to −10	9	0.942	75.00	0.110
−9	12	0.931	47.22	0.564
−8	20	0.894	50.00	0.500
−7	19	1.454	50.00	0.500
−6	26	1.263	66.67	0.077
−5	26	1.367	66.86	0.077
−4	43	0.936	58.26	0.178
−3	33	1.104	45.56	0.668
−2	20	0.818	34.07	0.875
−1	23	1.292	60.61	0.194
0	10	0.581	16.67	0.956
+1	18	1.022	39.38	0.775
2 and above	22	1.139	38.33	0.822
Pooled average			51.71%	0.316
Between temperature variation			12.909 12 d.f.	0.376

Data for the 1965–66 season have become available after the presentation of this report. The root double ratio is 1.473 for 1965–66 and 1.184 for the entire 1961–66 period (table III). The significance level, as computed in table IV, is 0.027 for the 1961–66 period. For the interior parts of the areas (table VII) the root double ratio is 1.273 for 1961–66 (1.642 for 1965–66) and the level of significance 0.009.

It is my pleasant duty to acknowledge the help and advice obtained from the Australian CSIRO weather modification team, especially in the early stages of planning this experiment.

Many people have been helpful to me in writing this report, including all my colleagues in this project and other workers in this field with whom I have discussed earlier versions. I am especially indebted to Professor J. Neumann's guidance and help and also to the suggestions of Mr. A. Gagin and Mr. K. S. Rosner.

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APPENDIX

On pooling tests and testing homogeneity. A comparison of a North seeded day with a Center seeded day is counted positive if the variable on the former day exceeds that on the latter. Let n_i and m_i be the sample numbers of North seeded and Center seeded days, respectively, in the ith of k groups. Let U_i denote the number of positive comparisons out of the $n_i m_i$ comparisons in the ith group, so that $U_i/n_i m_i$ is an unbiased estimate of the probability p_i that a comparison in group i be positive. It is well known that

$$\text{(A.1)} \qquad \operatorname{Var}\left[\frac{U_i}{n_i m_i}\right] = \frac{n_i + m_i + 1}{12 n_i m_i},$$

and that for samples which are not too small

$$\text{(A.2)} \qquad \frac{U_i}{n_i m_i}\left[\frac{12 n_i m_i}{n_i + m_i + 1}\right]^{1/2}$$

has a standard normal distribution if $p_i = 1/2$. This can be used to test $p_i = 1/2$, that is, the hypothesis of stochastic equality of the variables on both types of day, in what is known as the Wilcoxon-Mann-Whitney test ([17], section 9.6). The present form of the test is equivalent to the rank sum form as given in many textbooks.

Further, if it is assumed that $p_1 = p_2 = \cdots = p_k = p$, say, a weighted average estimate of p is

$$\text{(A.3)} \qquad \hat{p} = \frac{\sum_i 12 U_i/(n_i + m_i + 1)}{\sum_i 12 n_i m_i/(n_i + m_i + 1)},$$

whose variance is

$$\text{(A.4)} \qquad \operatorname{Var}\hat{p} = \left[\sum_i \frac{12 n_i m_i}{(n_i + m_i + 1)}\right]^{-1}$$

if $p = 1/2$. This allows the testing of hypothesis $p_1 = p_2 = \cdots = p_k = 1/2$ by means of the statistic

$$\text{(A.5)} \qquad \left(\hat{p} - \frac{1}{2}\right)(\operatorname{Var}\hat{p})^{1/2}$$

which is normally distributed under the hypothesis (if the samples are not very small). This pooled test is due to van Elteren [7].

Another test of the hypothesis $p_1 = p_2 = \cdots = p_k = 1/2$ makes use of the variance estimate

$$s^2 = \sum_i \frac{12U_i^2}{n_i m_i(n_i + m_i + 1)} - \hat{p} \sum_i \frac{12U_i}{n_i + m_i + 1} \tag{A.6}$$

which, under the hypothesis, has a chi square distribution with $(k - 1)$ degrees of freedom. This statistic is equal to the sum of squared deviations of the U_i/n_im_i estimates from their mean $\hat{p}$, inversely weighted by Var (U_i/n_im_i).

If either the $\hat{p}$ test or the s^2 test is significant, $p_1 = p_2 = \cdots = p_k = 1/2$ must be rejected. If only the former is significant, we may have $p_1 = p_2 = \cdots = p_k = p \neq 1/2$, the sign of the statistic indicating whether $p > 1/2$ or $p < 1/2$. If only the latter is significant we may conclude that the different p_i's differ from one another but *on the average* they are near 1/2.

Care must be taken in the use of these tests when $p_1 = p_2 = \cdots = p_k = 1/2$ is not true, because then the variance is not as described above.

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