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Effect of Noise on the Mathematical Parameters that Describe Isothermal Seed Germination[1]

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ABSTRACT

A mathematical model is proposed to describe the isothermal germination rate of seeds as a function of time. All environmental parameters were held constant with the exception of the sound-pressure level and the frequency of the impinging sound waves. Each single frequency sound has its own set of mathematical parameters that describe the differential germination rate as a function of time. Frequencies of 100, 1000, 2000, 4000, and 9000 hertz as well as broad band noise, all at 100 decibels, were used in the experiments.

A wealth of information concerning the effects of ultrasonic and audible sound on plants and seed germination is available in the literature (1–23, 25–30). These experiments were performed in the hope of increasing crop yield or of reducing the germination and growing time or both. The results of most of these reported experiments could not be reproduced because the experimenters could not or did not control all of the other parameters that entered into the biological process, and the results were mostly inconclusive as to whether sound had any effect.

The purpose of our study was to see if sound does indeed have any effect on the isothermal germination rate of seeds. We were not looking for larger crop yields or shortened growing times but rather for the effects of sound and, if possible, we hoped to describe these effects quantitatively. We have studied the effects of broad band noise and single frequency sound on the germination rate of turnip seeds and have been successful in controlling all environmental parameters that enter into this process. The only environmental parameters that were allowed to vary were the sound-pressure level and frequency. The data have been reproduced many times with groups of seeds varying in number from 400 to 1000. The superposition of these results yields the same approximate answers as each separate trial. A mathematical model is proposed to describe quantitatively the germination process. The confidence level and statistical significance of the superposed experiments are, of course, much greater than any one of the experiments because the results are so reproducible.

MATERIALS AND METHODS

The broad band noise was generated by using a Hewlett-Packard 8057A precision noise generator. The signal was fed into a McIntosh 75-w audio amplifier and then into Criterion 150A 30-w speakers. The resulting sound field was analyzed with a Hewlett-Packard 8055A filter set (31 Hz[2] – 16,000 Hz) coupled to a Hewlett-Packard 8062A impulse sound-level meter. The microphone was a calibrated Hewlett-Packard condensor microphone assembly model 15119A. A Hewlett-Packard audio oscillator model 200AB was used for the single frequency studies. A Taylor constant recording thermometer was used for the temperature. The temperature remained constant at 23 ± 1 C during the germination process.

The seeds (*Brassica rapa*) used for these experiments were classified as Turnip Seven FCX lot No. 1-14908 for the 1971 growing season. The moist growth chamber consisted of two pieces of filter paper in a Petri dish moistened with 12 ml of distilled water. Each Petri dish had 25 seeds plated out in a 5 × 5 matrix. The relative humidity in the growth chamber was near 100% as evidenced by the condensation on the lid. Sixteen to 32 Petri dishes were used per experiment.

The room in which the seeds were germinated was specially constructed to minimize the external noise and maximize the generated noise inside. The seeds were in darkness except for the light from a 40-w bulb 5 min of every hour while they were being read. All seeds were exposed to this same 40-w bulb, so all groups had the same environmental conditions with the exception of the sound field. The seeds were all moistened simultaneously and were read for the first time 11 hr after wetting. A seed was considered germinated when the root appeared from the seed coat. Every hour interval after the initial reading another reading was taken, and the total number of seeds germinated and the number that germinated in the last hour were recorded. These readings were continued through the 25th hr at which time the sound was turned off.

The control group was designated as the quiet group and was not subjected to the noise from the sound generator but only to the ambient noise in the building. The maximum ambient noise was measured to be 62 db (Table I). All SPLs for the noise group were 100 db. These groups were run many times and were quite reproducible. Most of these groups consisted of 800 seeds per experiment. In all, some 4,800 seeds were used to establish the validity of the quiet group. The other experimental runs consisted of a minimum of two 800 seed runs that produced consistent results up to a maximum of eight 400 seed runs. As far as the data analysis is concerned all runs were normalized to 1600 seeds per experiment. Over 28,000 seeds were used to establish the total data. The variety of continuous sound treatments are shown (Table II) for 25 hr with frequencies of 100, 1,000, 2,000, 4,000, and 9,000 Hz and broad band noise.

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[2] Abbreviations: Hz: hertz; db: decibels; SPL: sound-pressure level.

Sound treatments of less than 25 hr duration were: (*a*) 4,000 Hz sound exposure for 1 hr after the seeds had been in the moist germination chamber for 1 hr; (*b*) 2,000 Hz sound exposure for 6 hr while the seeds were in the moist germintaion chamber; the seeds were then dried with a fan and germinated 4 days later in the quiet environment; (*c*) 2,000 Hz sound exposure for the first 16 hr after which the sound was turned off; (*d*) 1,000 Hz sound exposure for the first 16 hr after which the sound was turned off.

RESULTS AND DISCUSSION

In attempting to find a mathematical model that would fit the data, many different theoretical curves were tried. The first attempt consisted of treating the frequency of seed germination as a radioactive decay process. In the radioactive decay model each seed has a certain probability of germinating in a given time period. Various combinations of parent and daughter relationships were tried to fit the data to the theoretical curve but all of the attempts resulted in failure. Several other polynomials and hypergeometric functions were tried as theoretical curves but no acceptable confidence levels were found.

The mathematical model that was found to fit all of the data is the familiar differential equation that describes autocatalysis (24). The germination rate is given by:

$$\frac{dN}{dt} = k_2(a_o - N)(f_o + N)$$

Table I. *Frequency Spectrum for Broad Band Noise and Quiet Environments*

Octave Band (Hz)	SPL (100 db)	SPL (Quiet)
Hz	*db*	*db*
32	84	55
63	98	53
125	98	55
250	94	46
500	93	39
1,000	92	36
2,000	92	33
4,000	87	25
8,000	76	22
16,000	60	21
Total SPL	100	62

where a_o has the physical significance of being the total number of seeds that will germinate under the given environmental conditions; f_o is a parameter that is related to the initial germination rate (a large value of f_o means a large initial germination rate whereas a small value corresponds to a small initial germination rate); k_2 is the rate constant (small values of k_2 mean a broad curve whereas large values mean a narrow curve); and N is the total number of germinated seeds and is, of course, time-dependent.

The best test that is usually used for curve fitting is the minimum chi square test that results from a least square fit of the data to the proposed mathematical equation. Table II shows the minimum chi square test in tabular form along with the various confidence levels. The best fit parameters a_o, f_o, and k_2 are also presented along with their standard deviations.

The confidence levels may appear rather low when compared to the acceptable values of 80% or more that biological scientists arrive at by subjecting the data to an analysis of variance. Such a test on the analysis of variance is in this case a trivial exercise, as can be seen from the data. Each set of data is obviously different from all others (Fig. 1).

When it comes to curve fitting, elementary particle physicists have chosen a 5% confidence level as the minimum acceptable level for the fit of a theoretical curve to experimental data. Confidence levels of 50% or more are normally considered excellent and in such cases the theoretical curve is accepted as a good mathematical model describing the particular situation.

A computer program was written to perform a least square and minimum chi square fit for the germination rate equation. The computer used is an IBM 370 system located at the Triangle University Computer Center. Some typical data of the number of seeds germinated per hour as a function of time are shown in Figure 1. The error bars on the data points represent the standard deviations. The curve drawn on each of these figures is a theoretical curve based on the proposed mathematical model. The germintaion rate model fits the continuous single frequency sound and the broad band noise data well.

The reaction rate depends upon the SPL and the frequency. The values of k_2 for the continuous 1000, 2000, 4000, 9000 Hz, and broad band noise vary greatly. Low values of k_2 correspond to very broad differential germination rate curves, whereas large values of k_2 correspond to sharply peaked and narrow germination rate curves. The maximum value of k_2 occurs for the 1000 Hz data (sound turned off at 16 hr) and the minimum value of k_2 occurs for the broad band noise data.

The number of seeds that can potentially germinate accord-

Table II. *Best Fit Mathematical Parameters for Each Sound Treatment*

Treatment	$k_2 \times 10^{-4}$	$\sigma_{k_2} \times 10^{-4}$	a_o	σ_{a_o}	f_o	σ_{f_o}	χ^2_{min}	Confidence Level
Quiet	3.64	0.21	1338	37	18.0	8.4	8.2	33%
100 Hz continuous	3.97	0.17	1511	39	0.0	2.6	7.6	51%
1000 Hz continuous	5.15	0.24	1446	38	6.3	4.5	2.8	82%
2000 Hz continuous	4.02	0.19	1553	40	52.4	9.6	5.9	42%
4000 Hz continuous	4.92	0.16	1547	40	0.57	2.1	4.2	90%
9000 Hz continuous	4.32	0.21	1501	39	14.2	4.1	7.2	53%
Broad band noise (20–20,000 Hz) continuous	2.12	0.11	1198	35	618.0	32	2.5	83%
4000 Hz, 1 hr	4.45	0.18	1396	37	4.1	2.7	5.1	56%
2000 Hz, 6 hr dried, germinated 4 days later in a quiet environment	3.05	0.13	1433	38	159.0	15	7.1	56%
2000 Hz off at 16 hr	3.69	0.24	1488	38	40.0	9.6	13.2	2%
1000 Hz off at 16 hr	9.68	0.37	960	31	0.0	1.9	11.1	5%

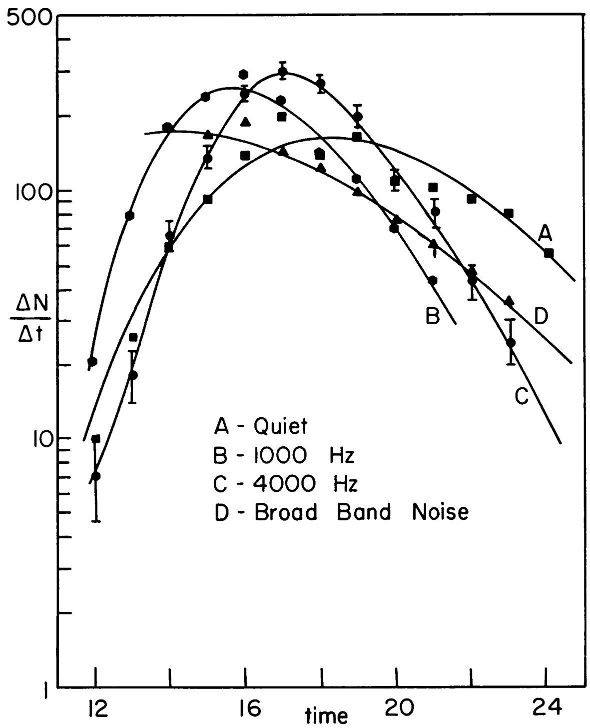

FIG. 1. Data points are the actual numbers of seeds that germinated in an hr interval as a function of time. The error bars on the 4000 Hz data represent the standard deviations of the data and are representative of the error associated with all of the other data points. The smooth curves are the theoretical reaction rate curves that are obtained by a least-square fit to these data points. The time is measured in hours after wetting.

ing to our model is given by a_o. The values of a_o are frequency dependent with the maximum value occurring at 2000 Hz and the minimum value occurring at 1000 Hz when the sound was turned off at 16 hr.

The values of f_o are small for most of the continuous single frequency sound treatments, being nearly 0 at 100 Hz, 0.57 at 4000 Hz, 6.3 at 1000 Hz, and 14.2 at 9000 Hz. The 2000 Hz f_o values are relatively large (40 and 52) compared to the other single-frequency treatments. With broad band noise the f_0 value was large (618), which seems to indicate that the initiation of germination is delayed by the broad-band noise. No seeds germinate until the 13th hr; when they do the maximum rate is reached rapidly (Fig. 1). A large value for f_o (159) is also found for the seeds that were exposed to 2000 Hz for 6 hr, then dried and germinated 4 days later in a quiet environment.

Looking over the data we can pick the worst case of seed germination, which is the 1000 Hz treatment that had the sound turned off at 16 hr. The germination rate drops abruptly after the sound is turned off, and the fit of the theoretical model is not good for this case.

Examination of Table II shows that each of the curves has its own unique set of parameters a_o, f_o, and k_2. The standard deviations are listed for each parameter and it is true that in some cases the values of k_2 are within a few standard deviations of each other, but in order to conclude that the curves are the same we would need all three parameters within at least two standard deviations. Figure 1 also shows that the peak times can be quite different. This is one additional parameter that is important.

One last important point concerning all of the seed data is the fact that when the sound was turned off at 25 hr and the seeds were left in the quiet environment for an additional 48 hr all lots achieved a 98 to 99% germination level regardless of the sound treatment. These data would suggest that the total yield is independent of sound treatment, provided the sound is turned off at 25 hr.

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