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Reflections on a Cumulative Record

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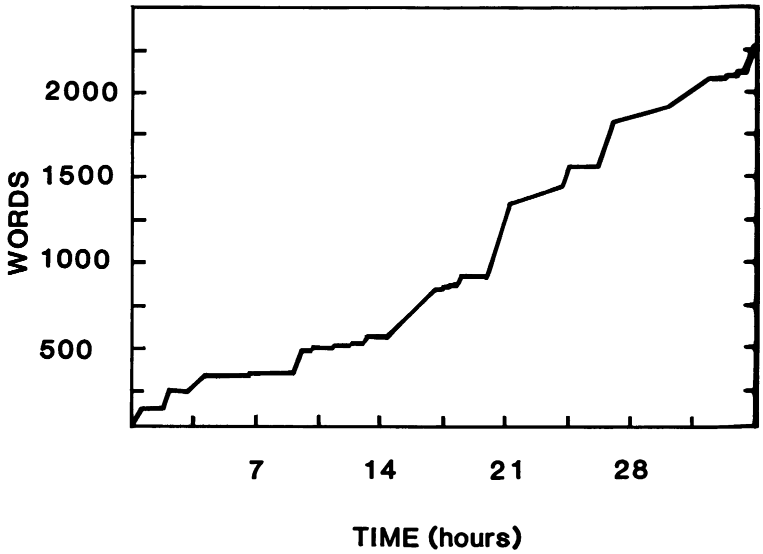

My introduction to operant conditioning came in the form of cumulative records of the four basic schedule types. Psychologists say that a good way to remember an item is to associate it with an image, especially an uncommon image. Were such a psychologist to subject me to a word-image association test today, the probe "operant conditioning" would evoke a collage of cumulative recorder/record, relay rack, and experimental chamber.

These emblems of my trade seem apt. The chamber epitomizes a concern for absolute control over stimuli, recognizing the quintessential importance of the environment in the control of behavior. The relay rack provides control along another dimension as well, time. It permits stimulus sequencing accurate to fractions of a second, with the ability to repeat, with modification, those sequences indefinitely. It symbolizes the step from a folksy type of natural history to a science that takes accuracy and replicability seriously. But what of the cumulative record? Often behavior is spread over time so broadly that our unaided senses can comprehend its regularities no more than they can the songs of whales or the play of ultraviolet and radio waves. The cumulative recorder can compress many hours of temporal patterns into a

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single page of spatial patterns. Here is magic indeed, of an order with speech-spectrographs and sub-nuclear cloud-chambers. How can it be that this powerful speculum has fallen into such disuse that Skinner (1976) could predict, "Evidently we shall not have long to wait for an issue of *JEAB* without a single cumulative record!" (p. 218).

Perhaps the answer is sociological. Perhaps it is economic—a good recorder costs about as much as a good computer. But my purpose here is not to answer the question of why we no longer favor this lovely device, but to ponder what we had when it was ours.

Our text will be the words of Skinner (1969): "Unlike hypotheses, theories, and models, together with the statistical manipulations of data which support them, a smooth curve showing a change in probability of a response as a function of a controlled variable is a fact in the bag, and there is no need to worry about it as one goes in search of others" (p. 84).

First, we are faced with a problem of interpretation. Does this passage encompass cumulative records? These are often smooth, and show changes in rate of response, which Skinner took to be equivalent to the probability of a response. But time, the abscissa of cumulative records, is not a controlled variable, and strictly not even a controlling variable. Events that happen in time bring about other events, not time itself. I think Skinner (1976) appropriately finessed the issue by saying of a cumulative record, "It *suggested* a really extraordinary degree of control . . ." (p. 218; emphasis added), even though the things that effected the control were themselves seldom plotted on the x-axis. Whether we should take credit for a fixed-interval scallop as evidence of an "extraordinary degree of control," any more than we applaud a child who throws a ball into the sky for his or her perfect parabola, will not be argued here. Skinner seldom plotted controlled variables such as body weight or luminosity on the x-axis, and often presented cumulative records that measured time there. The gist of his research therefore seems to place cumulative records in the secure position of "a fact in the bag." Hypotheses, theories, and models are left outside, elusive and mutable.

REPRESENTATIVE RECORDS

But science is not just the gathering of facts. Our bags are not big enough to hold all the facts we might collect, and once they got half full, retrieving a particular fact would be like finding a pair of socks at the bottom of an enormous duffel. Skinner himself noted that, although we could take motion pictures and sound recordings of animals, this would not constitute a science of behavior: We must abstract, classify, and replicate (1938, pp. 8–9). We must compress the overabundance of information, omitting unnecessary details. But the ability to do this rests on the availability of a theory to tell us what is necessary, or a compression engine that implicitly embodies such criteria. The cumulative recorder is one such device, even though anyone who has had to cope with the hundreds of yards of output from a single experiment knows that even it is not good enough. Of course, one can select "representative" records, but that is another trimming of the data based on implicit criteria for what is representative. Skinner once ganged a number of cumulative recorders together to further condense the data (see Skinner, 1972, pp. 512–513), but something made him abandon the idea, and assert instead the importance of data from individual subjects.

Our science is not about particular cumulative records any more than mathematics is about particular numbers. But if we are interested in the properties of classes of behavior, we need a way to characterize and sort our data. If we want "facts in the bag," we need to know whether the eleventh and twelfth scallops of a session are two facts or one. How do we decide? My dictionary defines "scallop" as "one of a series of rounded projections." That won't get us far beyond distinguishing three classes: rounded, too straight to be rounded, and too angular to be rounded. Since this seems to categorize the signatures of three basic schedules (fixed-interval, variable-interval [or -ratio], and fixed-ratio), it might be enough if all we wanted was to postdict which contingencies generated the record. If we want subtler analyses, we need more explicit criteria for curvature. These are provided by indices such as the "quarterlife" and "index of curvature."

But such indices are *ad hoc,* and have not made a significant contribution to experimental analyses. Another possibility is to generate a mathematical model of the average curve. But properties of an average curve may not represent properties of the individual curves (Hanson & Killeen, 1981). Descriptions at the level of the individual must often be different than descriptions at the level of the aggregate. We must decide which we are most interested in. The cumulative recorder forestalls that decision by giving us all, and leaving it to us to decide what to take.

THE RECORDER AS FILTER

Skinner offered a possible criterion for the selection of records when he praised smooth curves. Earlier (Skinner, 1935), he had emphasized experimental control and an optimal level of observation as means for generating such orderly data. But the cumulative recorder itself forces a particular level of observation. It tends to make curves smooth by picturing not rate, but the integral of rate over time, thus rectifying the data by prohibiting negative slopes. Furthermore, it is a "low-pass filter," emphasizing slower changes in behavior, and compressing high rates of responding. Rates are inferred from the slope of the records, that is, the angle they make with the horizontal. If this slope changed proportionately with response rate, it would give us an unbiased picture of rates. But it does not. The angle is part of a triangle whose height measures the number of responses and whose base measures time. It is the angle whose tangent is responses per minute. How does this "arc tangent" change as response rate changes? To find out we take its derivative with respect to rate, and that is $1/(1 + B^2)$, where B is response rate. This shows us that the sensitivity of the recorder decreases as the *square* of response rate, a radical compression indeed!

VARIETIES OF RECORD

But I cavil. The cumulative recorder did what nothing else at the time could do, and the data filters that were a byproduct of its machinery—a synchronous motor and stepping relay—did not seriously undermine the inferences that many (e.g., Ferster & Skinner, 1957) have been able to derive from its records. But now we are not limited to such simple machinery, and should experiment with other types of displays. Rachlin (1965) devised a recorder with a cam cut as a logarithmic spiral, that would carry the pen to the top of the sheet with ever-decreasing velocity as a function of time, while a response would step the paper along the x-axis and reset the pen. This machine plotted interresponse times, with a compression of long ones. The derivative of the logarithm of B is 1/B. This is a more moderate compression than that effected by a cumulative record, but one that reachs an absolute ceiling at the top of the page. Blough (1963) reported a technique for plotting interresponse times on an oscilloscope screen; the x-axis could be stepped as a function of time, or of responses, or of other variables. I myself have considered having responses charge a capacitor that discharges slowly with time, and plotting the voltage across the capacitor on an oscilloscope, thus displaying an exponentially-weighted moving average of response rate. If the time-constant of the circuit were properly adjusted, it might mirror that of the subject (cf. Real & Dreyfus's "levels of aggregation," 1985), and reveal regularities not before seen.

With computers, anything is possible, but little has been tried. One recent exception is provided by Hinson and Staddon (1983), who plotted "clock-spaces" to track the choice behavior of pigeons. Many other different types of graphs have appeared in our journals, but most of them have been the result of post-hoc analysis, not real-time transduction.

But why would we want a real-time record? What is the purpose of graphs—what do they accomplish that words will not? Are they not a translation of the data to an "other level of observation, described in different terms, and measured, if at all, in different dimensions" (Skinner, 1969, p. vii)? Here Skinner's position on the nature of science gives the most cogent answer. Scientists are behaving organisms, and such displays provide discriminative stimuli that control scientific behavior. As Wood (1980) noted, these displays bring the behavior of the scientist more effectively under the control of the organism.

ART AS SCIENCE

But what is the nature of that control? How do we communicate it? If we cannot, is it scientific? But need it be "scientific"? Is there not room in our business for art? "Elegance" and "aesthetic appeal" have always been an important part of the best scientific research. The *Division 25 Recorder* of the American Psychological Association uses cumulative records as a cover design, and *Science* often uses a figure from one of its articles as its cover. The process of research must be rewarding or it will extinguish as soon as extrinsic rewards, such as tenure, are exhausted. Cumulative records and other such displays are important as S^D's. I would argue that they are equally important as S^R's.

But once we admit an aesthetic justification, will abstract expressionism be far behind? Perhaps, but perhaps that will be all for the good. Stimuli need not stand in one-to-one correspondence with textual stimuli, or with any other kind of stimuli, for them to be effective in evoking useful scientific behavior. Many great scientists, from Einstein to Shepard, have been visual thinkers; it is time for us to liberate our science from the left hemisphere.

What of modalities other than vision? The cumulative record graphs temporal changes, but those are much better perceived by the ear than the eye. Why not connect a slow-motion tape recorder to each experiment, and listen to the patterns? Perhaps in stereo, with alternate responses on different channels. This would provide a much more effective condensation of the data, and the sound of schedules might control our behavior more effectively than the sight of them. The greatest problem with this technique would be publishing the records. It might be possible to include a strip of cassette tape with reprints of articles, leaving it to the reader/auditor to splice it into his or her machine. Computer and media technology may soon provide better solutions. But publication of the records isn't critical. After all, what portion of the miles of visual records that have been cumulated have been published? This is performance art, whose primary purpose is to instruct and entertain the experimentalist; the archival record is of secondary importance. Acoustic records may be replayed as the experimenter reviews the day's data or composes the article. Then, like most visual records, they can be stored away until spring lab-cleaning, or brought to a poster and tape session (Gleeson, Freeman, & Lattal, 1985).

THE CARDINALITY OF CUMULATIVE RECORDS

Cumulative records, and all other "smooth curves," present a paradox: Rendering a phenomenon as a "smooth curve" *increases* by *an order of infinity* the complexity of our descriptive task.

The mathematician Cantor showed that different processes may lead to different orders of infinity, or "cardinality" (Cantor, 1915; Dauben, 1979). Processes that can be put into one-to-one correspondence with the natural numbers yield a "denumerable" infinity, to which he assigned the Cardinal Number $\aleph_0$ ("aleph sub null"). The number of possible theories constitutes a denumerable infinity, as each letter of them may be mapped against a number, as is done, for example, by a word-processor. (More technically, each symbol can be mapped to a different prime number; the product of those primes constitutes a unique tag for that theory, different from every other theory, but a member of a denumerable set.)

But the number of points in a line segment, and the number of curves in a plane, are too great to map against the natural numbers. When we attempt the mapping, we will find that no matter how we assign the numbers, there remains an infinity of points, or of curves, between consecutive numbers. Their Cardinal Number is greater than $\aleph_0$; it is the Cardinal Number of the continuum, 2 raised to the power $\aleph_0$. By turning away from theories to smooth curves, we thus generate an exponential increase in the number of things we have to deal with. To know a theory is to know infinitely more than to know a smooth curve!

"What's the trick ?" you ask. Surely there's sophistry at work! There are considerations, but there is no trick. The cumulative record is saved from a higher cardinality to the extent that it is *not* smooth. Because our equipment digitizes behavior, each response increments the cumulative record by one unit. If we similarly digitize time, say by advancing the paper a unit distance every 10 milliseconds, then all information would be coded in denumerable variables, the lines between points being unessential filler, and cardinality would be restored to $\aleph_0$.

Here then is the paradox: By making a smooth curve jagged, we make it infinitely simpler.

Here is the resolution: It is simpler only in the sense that there are infinitely fewer of its type to discriminate it from. If science were ideographic, concerned with every manifestation, this would be the sense that mattered. But science is nomothetic, seeking regularities, eager to incorporate different manifestations into a class if the features that distinguish them are minor enough, and the family resemblance with other members of the class good enough.

And this is where models come into play. A smooth curve is simpler than a jagged one in the sense that it may be described by a model that has fewer parameters. To say that a scallop is a hyperbola is simpler than to say that it is a hyperbola with a 0.8 mm jump 4.56 mm from its origin. To realize the simplicity of smooth curves, we must invoke mathematical models to represent them.

ANALYSES THAT ARE GOOD ENOUGH

Like all artifacts, theories and models are imperfect. They are ways of summarizing effects, and thus suffer at least from incompleteness, if not from more serious defects. But not every deviation from prediction should be the occasion for the rejection of a model. If we required that there be no error variance, we would need to constrain all the variance out of behavior by stringent control, or we would have to tolerate as many models as there are data sets. Serlin and Lapsley (1985) discuss this "Good-Enough" principle in psychological research. As we increase the power of our experiments, as by increasing the number of subjects, it becomes easier to reject the null hypothesis, so that for a sufficiently powerful experiment one can always reject the null hypothesis. This distemper of methodology may be avoided by requiring that an effect be of some minimal magnitude, and below that, the null hypothesis should be considered good enough. Similarly, deviations from some summary description, such as "hyperbola," or "rate constancy" or "matching" must exceed some threshold before the simpler description ceases to be good enough. How much latitude is acceptable is determined by the mood of the scientific community at the time, and the ability of competing descriptions to do better. In most cases, though, our indulgence should be greater than the minimal allowed by statistical tests.

Just as theory constrains the selection of data, data constrain the selection of theory. "Facts and theories, it seems, are related symbiotically: The quality or utility of each depends on the other." (Rider, 1985). And thus must we bootstrap our way to knowledge, continually reviewing theory in light of new data, and reevaluating data in the light of new theory.

The cumulative recorder provides simple descriptions of behavior; but are they good enough descriptions? For some things, yes. For others, no. The record pictured on the first page of this article reports time on task while writing this article. Does it provide an adequate abstract of the article? Only of one aspect, and that aspect is perhaps the least important thing about verbal behavior. Like many products of American technology, the cumulative recorder's shortcomings are due less to intrinsic problems than to lack of competition. What we need are more types of records, each providing a different perspective on that most protean of phenomena, the behavior of organisms.

SUMMARY

The cumulative record does not provide an unbiased summary of behavior. It abstracts certain features and, of these, highlights some and obscures others. It has proliferated because those biases have been useful for the analysis of some types of behavior. For other behavior where the cumulative record is ineffective, such as concurrent responding, other displays have evolved. It is argued here that there should be more experimentation with non-standard displays, to increase the number of analytic tools in our repertoire. The purpose of such displays is not only to provide discriminative control of the scientist's behavior, but also to reinforce that behavior. Both functions should be recognized, as should the corollary: Choose instruments carefully, for they will shape what aspects of the data you consider important.

Smooth curves are lovely to look at, but difficult to describe without an appropriate model. The choice of the model that we employ is constrained by the data. In turn, the control exerted on our behavior by the data depends on the form of display, and the theory—explicit or implicit—that guides the choice of a display. The data-theory system thus forms a dialectic, and the scientific process an oscillation between reconstruction of theory and reconstrual of data. The oscillations are damped by a "good-enough" principle, by which we adhere to a viewpoint and a data set until their incongruities exceed some threshold. The size of that threshold depends, in part, on the cost of switching to alternate theories or of ignoring certain data sets. Displays such as the cumulative record not only embody theoretical decisions about the importance certain aspects of the data (in this case, temporal patterns from single operant repertoires emphasizing low rate changes), they also involve costs, both in acquiring the devices that generate them, and in educating the audience in their utilization. By their existence, then, they slow innovation. But inevitably they are subject to refinement, as they coevolve with the data that they represent.

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