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CONSTRUCTION OF EQUAL-HUE DISCRIMINABILITY SCALES FOR THE PIGEON[1]

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Equal-hue discriminability steps for the pigeon are shown as tabular entries that can be summed or interpolated to produce sequences of equal discriminability steps of various step size. Equal-hue discriminability sequences can be constructed where the number of stimuli and spectral range are specified, or where an interval in one spectral region is to be equated to an interval in another spectral region.

Key words: wavelength discrimination, discrimination, generalization gradients, stimulus control, stimulus generalization, key peck, pigeons

Pigeons probably have a dominant visual sense, and the wavelength continuum is an often-used physical continuum in learning and conditioning experiments with pigeons. In order to use wavelengths of light properly as stimuli in training and testing, the wavelengths should be selected so that the intervals between adjacent stimuli represent equally discriminable intervals. If the wavelengths do not represent equally discriminable steps, then in a generalization test, for example, the ensuing extinction will be more rapid in some spectral regions than in others. The result may be a distortion of the shape of the generalization gradient. Test stimuli equally spaced on the physical wavelength continuum will produce a disproportionate loading of stimuli in some hues because the physical continuum of wavelength is not isomorphic with the psychological continuum of hue. Likewise, the interval between training stimuli is critical. Hanson (1959) showed that the size of the wavelength spacing between a positive and negative stimulus affected the shape of the generalization gradient. Thus, only if the discriminable spacing among training stimuli is equated, will the generalization gradients from different spectral regions be comparable.

This article describes a procedure for spacing wavelengths of monochromatic light so that the intervals between adjacent stimuli will be equally discriminable intervals for the pigeon's perception of color.

EXPERIMENTAL BASIS

A hue discrimination experiment was conducted over 3.5 yr. (For a more complete description of the procedure and analysis, see Wright, 1972, 1974.) Three pigeons judged whether two halves of a split field were equal in hue or different in hue. These judgements were made in a yes/no choice procedure. They observed the split field behind the center key and were required to make an observing response on the center key. Following the observing response, a choice response on one of two side keys was required. A peck on the right side key was tantamount to a "yes" response that the two field halves were different in hue. A peck on the left side key was tantamount to a "no" response that the two field halves were not different in hue. Correct "yes" and correct "no" responses were occasionally reinforced with mixed grain. Incorrect choices, a right-side key peck when the two field halves were equal in wavelength or a left-side key peck when they were unequal in wavelength, never produced reinforcement. Reinforcement, a nonreinforced correct choice, or an incorrect choice was followed by an 8-sec intertrial interval. During each session, the left-field half was always of the same wavelength. The right-

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field half varied in wavelength from trial to trial; on 100 trials, it was of a wavelength equal to the left-field half; on 500 trials, it was of a wavelength shorter than that on the left-field half. The shorter wavelengths took on one of five values, and each of these five shorter wavelengths were presented for 100 trials each session. These shorter wavelengths were selected so that the greatest wavelength difference between the two field halves would produce slightly less than perfect performance, and so that the smallest wavelength difference would produce slightly greater than chance performance. The 100 trials of each of the five wavelength differences, and the 100 trials of the no-wavelength difference were intermixed each session. The reinforcement probabilities for correct choices were varied to alter the subjects' bias toward making a choice response on one or the other of the two side keys. An example of these data is shown in Figure 1 for a reference wavelength of 590.4 nm and a comparison wavelength of 587.9 nm. Correct right-side key choices on the ordinate are plotted against incorrect right-side key choices on the abscissa. This is a plot of hits *versus* false alarms, where a hit is defined as correct identification of a wavelength difference. One point came from each of 11 sessions. Similarly there were 11 points for each of the other four wavelength differences (not shown) that were also presented during the sessions in which the data shown in Figure 1 were collected.

By making side-key bias a parameter of the experiment, bias and discriminability were separated to obtain bias-free measures of discriminability. Normal deviate scales are used for the hit and false-alarm rates, and such scales regularly produce linear receiver operating characteristics (ROC), illustrated by the ROC in Figure 1. The linear ROCs were fitted by eye and the point where they cross the dotted line in Figure 1 (the negative sloping diagonal) is the point of equal bias. This point of equal bias or no bias can be thought of as the point where bias does not adversely affect the assessment of discriminability. The discriminability measures, d′, come from signal-detection theory and are the normal deviate values of correct right-side key choices (hits) minus the normal deviate values of incorrect right-side key choices (false alarms). These d′ values, computed at the point of no bias, were then plotted as a function of the wavelength difference used to produce them. At each reference wavelength, five such points were obtained, one for each of the wavelength differences presented. One example of the psychometric functions, as they are called, from this experiment is shown in Figure 2. The point next to the lowest one is from Figure 1, and it is the d′ value for the intersection of that ROC with the negative diagonal. The d′ values for the other four points in Figure 2 were calculated in a similar

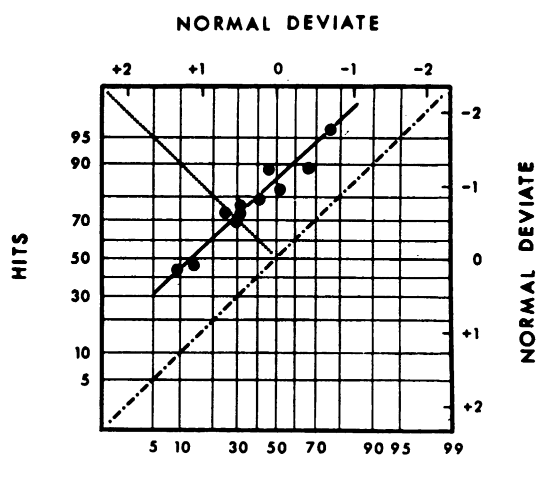

Fig. 1. One of the five receiver operating characteristics for Pigeon 287 at a reference wavelength of 590.4 nm. See text for details.

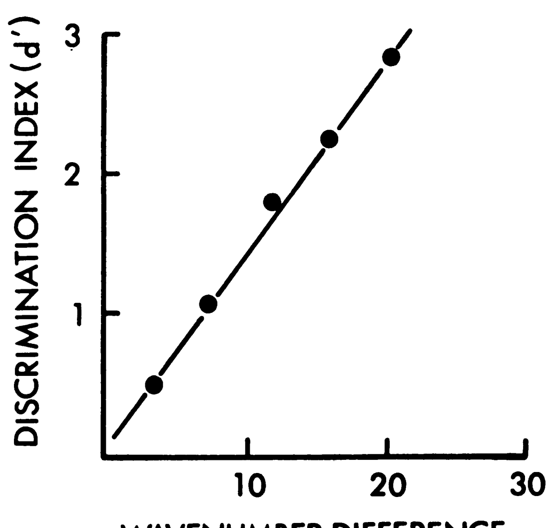

Fig. 2. Psychometric hue-discrimination function for Pigeon 287 at reference wavelength of 590.4 nm.

manner and were plotted as a function of the wavenumber difference, where wavenumber is the reciprocal of wavelength. This psychometric function is typical of the 20 psychometric functions from each of the three subjects in this experiment. They were shown to be linear (median correlation coefficient of 0.99) and pass through the origin of their graphs, and so could be summarized by their slope values. A steep-sloping psychometric function indicates good discriminability; as wavenumber difference increases discriminability, (d′) increases very rapidly. By contrast, a shallow-sloping function indicates poor discriminability; as wavenumber difference increases, discriminability increases very slowly. Linearity and zero intercept of the psychometric functions has far more importance than just providing convenient summary statistics. It forms the theoretical foundation (Wright, 1974) that permits freedom of choice in the absolute size of the discriminability step, and allows equal discriminability scales of different step size to be generated from a single set of values.

Figure 3 is the psychophysical hue-discrimination function, or relative sensitivity function (Wright, 1974), and is to be distinguished from the previously shown psychometric hue-discrimination functions. Plotted in Figure 3 are the mean reciprocals of the slopes of the psychometric hue-discrimination functions. At each of the 20 spectral points investigated in this experiment, the slope reciprocals were averaged over the three subjects. The range markers shown in Figure 3 show the ranges of slope reciprocals for the three subjects. The smooth curve in Figure 3 was drawn through the points by eye, and represents the author's best judgement of the pigeon's hue discriminability over the continuous wavelength interval from 470 to 660 nm. The slope reciprocal is used instead of the slope itself because the critical variable is relative sensitivity, and relative sensitivity between two spectral regions is equal to the ratio of slope reciprocals of these regions (Wright, 1974, p. 329, Eq.[3]). Wavelength intervals need to be chosen so that the hue difference produced by one wavelength difference is equal to the hue difference produced by another wavelength difference. Relative sensitivity for any two spectral points is a ratio of these wavelength differences, and is equal to the ratio of slope reciprocals. This

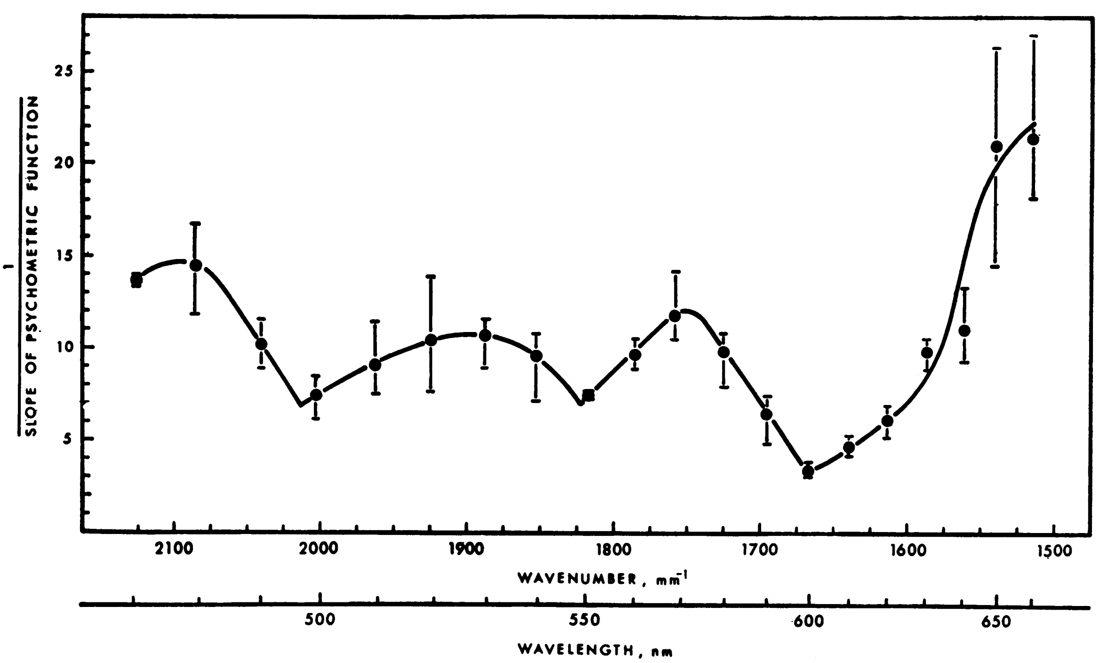

Fig. 3. Mean hue-discrimination function. The slope reciprocals for each of the 20 reference wavelengths (λ) were averaged over the three pigeons and plotted on a linear scale of wavenumber (1/λ). The range of the three subjects' slope reciprocals is shown by the markers at each spectral point. The smooth curves were drawn and fitted by eye.

Table 1

Equal-hue discriminability steps in wavenumber ($1/\lambda$) and wavelength (λ) and reciprocals (K) of discriminability measures for pigeons over the 660- to 470-nm spectral region.

$\frac{1}{\lambda}$(mm^{-1})	λ(nm)	K	$\frac{1}{\lambda}$(mm^{-1})	λ(nm)	K	$\frac{1}{\lambda}$(mm^{-1})	λ(nm)	K	$\frac{1}{\lambda}$(mm^{-1})	λ(nm)	K
1515	660.1	21.7	1658	603.1	3.6	1791	558.3	9.3	1957	511.0	9.3
1525	655.7	21.4	1660	602.4	3.6	1795	557.1	9.0	1961	509.9	9.2
1535	651.5	20.3	1662	601.7	3.5	1799	555.9	8.7	1965	508.9	9.0
1544	647.7	19.0	1664	601.0	3.4	1803	554.6	8.4	1969	507.9	8.8
1553	643.9	17.1	1666	600.2	3.3	1807	553.4	8.1	1973	506.8	8.7
1560	641.0	15.2	1668	599.5	3.4	1811	552.2	7.8	1977	505.8	8.5
1567	638.2	12.5	1670	598.8	3.7	1815	551.0	7.5	1981	504.8	8.3
1573	635.7	11.1	1672	598.1	4.0	1818	550.1	7.2	1985	503.8	8.1
1578	633.7	9.7	1674	597.4	4.2	1821	549.2	7.0	1989	502.8	7.9
1583	631.7	8.9	1676	596.7	4.4	1824	548.2	7.1	1993	501.8	7.7
1587	630.1	8.3	1678	596.0	4.7	1827	547.3	7.5	1997	500.8	7.6
1591	628.5	7.9	1680	595.2	4.9	1831	546.2	7.9	2001	499.8	7.4
1595	627.0	7.5	1682	594.5	5.1	1835	545.0	8.3	2004	499.0	7.2
1599	625.4	7.1	1684	593.8	5.4	1839	543.8	8.6	2007	498.3	7.0
1602	624.2	6.8	1687	592.8	5.7	1843	542.6	8.9	2010	497.5	6.9
1605	623.1	6.6	1690	591.7	6.1	1847	541.4	9.2	2013	496.8	6.9
1608	621.9	6.4	1693	590.7	6.5	1851	540.2	9.4	2016	496.0	7.3
1611	620.7	6.1	1696	589.6	6.8	1855	539.1	9.6	2019	495.3	7.6
1614	619.6	5.9	1699	588.6	7.2	1859	537.9	9.9	2023	494.3	8.0
1617	618.4	5.7	1702	587.5	7.5	1864	536.5	10.1	2027	493.3	8.5
1620	617.3	5.6	1705	586.5	7.8	1869	535.1	10.3	2031	492.4	9.0
1623	616.1	5.4	1708	585.5	8.2	1874	533.6	10.4	2035	491.4	9.6
1626	615.0	5.2	1712	584.1	8.6	1879	532.2	10.6	2039	490.4	10.1
1628	614.3	5.1	1716	582.8	9.0	1884	530.8	10.6	2044	489.2	10.7
1630	613.5	5.0	1720	581.4	9.5	1889	529.4	10.7	2049	488.0	11.3
1632	612.8	4.9	1724	580.1	10.0	1894	528.0	10.7	2054	486.9	11.9
1634	612.0	4.8	1729	578.4	10.5	1899	526.6	10.7	2060	485.4	12.6
1636	611.2	4.7	1734	576.7	11.2	1904	525.2	10.6	2066	484.0	13.2
1638	610.5	4.6	1739	575.0	11.7	1909	523.8	10.6	2072	482.6	13.7
1640	609.8	4.5	1744	573.4	12.0	1914	522.5	10.6	2078	481.2	14.2
1642	609.0	4.4	1750	571.4	12.0	1919	521.1	10.5	2085	479.6	14.4
1644	608.3	4.3	1756	569.5	11.9	1924	519.8	10.4	2092	478.0	14.5
1646	607.5	4.2	1762	567.5	11.6	1929	518.4	10.2	2099	476.4	14.5
1648	606.8	4.1	1767	565.9	11.2	1934	517.1	10.1	2106	474.8	14.4
1650	606.1	4.0	1772	564.3	10.8	1939	515.7	9.9	2113	473.3	14.2
1652	605.3	3.9	1777	562.7	10.4	1944	514.4	9.8	2120	471.7	13.9
1654	604.6	3.8	1782	561.2	10.0	1949	513.1	9.6	2126	470.4	13.5
1656	603.9	3.7	1787	559.6	9.6	1953	512.0	9.5			

ratio (relative sensitivity) is invariant with changes in the absolute size of the wavelength difference (and hence the magnitude of the hue difference) because the psychometric functions are linear and are of zero intercept. This is a particularly important result for generating scales of uniform hue discriminability; only when relative sensitivity is invariant can equal-hue discriminability intervals, such as the entries in Table 1, be summed or interpolated to generate equal-hue discriminability scales of other step sizes. As it turns out, scales of a variety of step size can be constructed from the Table.

TABLE 1 CONSTRUCTION

Table 1 was constructed from the smooth curve of Figure 3. A large version of Figure 3 was used to resolve accurately the slope reciprocal values. The wavelength interval between entries in Table 1 varies somewhat. The intervals are equal-hue discriminability steps. The table was constructed by arbitrarily choosing the first interval of the sequence (1525 mm^{-1}—1515 mm^{-1}). The next interval begins at 1525 mm^{-1} and is determined by calculation. The ratio of this interval ($X - 1525$ mm^{-1}) to the K value for 1525 mm^{-1} was made proportional to the ratio of the first interval ($1525\ mm^{-1}$–$1515\ mm^{-1}$) relative to the K value of $1515\ mm^{-1}$.

$$\frac{X - 1525\ mm^{-1}}{21.4} = \frac{1525\ mm^{-1} - 1515\ mm^{-1}}{21.7} \quad (1).$$

The equation is solved for X and its solution is the wavenumber of the next interval, $1535\ mm^{-1}$. Its slope reciprocal, 20.3, was read from the smooth curve of Figure 3. This wavenumber and K value were then substituted into the left-hand side of Equation 1 and the wavenumber for the next interval calculated. This step-by-step procedure was continued for all of the 151 values shown in Table 1. Most evidence and arguments (Hailman, 1967; Wald, 1965; Wright, 1972) favor using a wavenumber scale for such calculations, rather than a wavelength scale, and a wavenumber scale was used in this case. Equal wavenumber differences produce a gradual decrease in wavelength difference as the differences progress from long to short wavelengths. Wavelengths (reciprocals of wavenumbers) are shown in Table 1 because most experimenters regularly work with and think in wavelength not wavenumber.

The method used to construct Table 1 can be used to construct equal-hue discriminability scales. The right-hand side of Equation 1 can be any arbitrarily chosen interval, and the left-hand side can be the interval-to-be-calculated. If one wishes to space several stimuli within a specified interval, *e.g.*, for a generalization test, then the right-hand side of Equation 1 should be a ratio of mean spacing (total wavelength interval divided by one less than the number of test stimuli) to the mean K. A problem arises when choosing a K for the left-hand side of Equation 1. This K value should also be the mean value for the interval-to-be-calculated, but since its extent is unknown before calculation, one has to approximate it with the K for the beginning of the interval. The interval calculated will be in error, depending on the size of the interval and the rate change of the K over the interval. The first calculation of the interval can serve as the first approximation. The mean K can be calculated and the interval recalculated. This recalculation procedure can continue until there is no appreciable change in the size of the calculated interval. Discriminability scales thus constructed are time consuming to calculate and are somewhat subject to error. The next section describes a scalar construction procedure that relies on a simple interpolation of the tabular entries, and which can be used faster and more accurately.

SCALE CONSTRUCTION

The easiest way to construct an equal-hue discriminability scale is to use the wavelengths in Table 1 corresponding to consecutive entries, every other entry, every third entry, *etc.* The K values can be disregarded when using the scalar construction methods of this section.

If wavelengths are desired that are intermediate between entries in Table 1, then interpolation can be used to construct the scale. Each stimulus of the series is separated by the same number of entries (including fractions) of Table 1. The following examples illustrate the use of this interpolation procedure.

Example: if the first interval of a series of equally discriminable intervals is the interval 570.0 nm to 574.0 nm, then the number of discriminability steps in this interval will determine the number of discriminability steps separating the rest of the stimuli in the scale. The number of discriminability steps in this interval 570.0 to 574.0 is: $(571.4 - 570.0)/(571.4 - 569.5) + (573.4 - 571.4)/(573.4 - 571.4) + (574.0 - 573.4)/(575.0 - 573.4)$, or $0.74 + 1.0 + 0.38 = 2.12$. The next interval of the series will be 2.12 steps from 574.0 nm. The fraction of a step from 574.0 to the next entry is: $(575.0 - 574.0)/(575.0 - 573.4) = 0.63$, and therefore the desired wavelength is $(2.12 - 0.63)$, or 1.49 steps from this entry. The interval 576.7 to 575.0 is one step. Therefore, the next wavelength in this series is 0.49 of the interval 578.4 to 576.7, or $(X - 576.7)/(578.4 - 576.7) = 0.49$, and therefore the desired wavelength is 577.5 nm. This process is continued and other wavelengths of this series correspond to successive 2.12 entries or steps in Table 1.

Experimenters who wish to space several stimuli within a wavelength interval (*e.g.*, for a generalization test) need only to determine how many tabular entries will be between adjacent stimuli of the entries, and then calculate the wavelengths of the stimuli by interpolation.

Example: if one wants to conduct a generalization test over the wavelength interval 580 to 620 nm with 10 test wavelengths in this interval, then add the entries and fractions of entries between 580 and 620 nm (45.42) and divide by (10 − 1) or 9 to get the number of steps (5.05) between adjacent test wavelengths. Then, by linear interpolation, the wavelength value can be calculated corresponding to multiples of 5.05 steps from 580 nm. The 10 wavelengths thus calculated are: 580.0, 586.5, 591.8, 596.1, 599.6, 603.3, 607.0, 610.7, 614.5, 620.0 nm.

This method and table should facilitate rapid calculation of equal-hue discriminability scales for pigeons; it is hoped that validity and precision of experimental results will be enhanced by eliminating the variable of discriminability differences.

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