

An interval scale of brightness for the pigeon

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Pigeons were required to discriminate between *identical* and *different* pairs of lights in a *same/different* signal-detection task. If the two lights projected onto the stimulus field, which was mounted behind the center response key in a three-key chamber, were identical in intensity, a single peck on the left key was reinforced with food. If the two lights differed in intensity, right-key pecks were reinforced. Each pigeon experienced all possible pairs (45) of 10 levels of light intensity. The percentage of correct responses was taken as an ordinal measure of the brightness difference between the lights constituting a pair, and was used to determine interval scales of brightness in the pigeon. The brightness scale for pigeons was similar to that obtained from human subjects in judging brightness differences.

Although the relation between brightness and luminance has been studied extensively in humans (Marks, 1966, 1968, 1971, 1972; Marks & J. C. Stevens, 1966; S. S. Stevens, 1966; S. S. Stevens & J. C. Stevens, 1960), there have been only a few attempts to determine the function relating brightness to luminance in animals. Herrnstein and Van Sommers (1962), in attempting to determine if a power function (Stevens's law) related brightness to luminance, trained pigeons to respond at different rates to lights of different intensities. The response rates at these training intensities were constrained such that response rate was a power function of intensity. When testing at intermediate intensities, Herrnstein and Van Sommers found that the intermediate stimuli elicited response rates that were consistent with a power law formulation. However, as Blough (1965) pointed out, the power law was, in a very direct sense, "built into" the response measure. Furthermore, when Blough analyzed Herrnstein and Van Sommers's data, he found that response rate was closer to a logarithmic, rather than a power, function of intensity. In general, to use response rate to measure sensation in a technique such as this, one must assume that response rate is proportional to sensory magnitude. Considering the number of factors that are known to influence response rate, the probability of such a correspondence is impossible to assess.

Boakes (1969) employed a bisection technique to scale brightness. In this procedure, pigeons were trained to peck a right key for a bright stimulus and a left key for a dim one. Intermediate stimuli were then presented to determine the stimulus that produced equal pecking on both keys. Presumably, this stimulus bisected the sensory interval. But, as Blough and Blough (1977) pointed out, response factors such as position preference can alter the

probability of a side-key response and influence the location of the bisection point. Since there is no easy way to control or compensate for such potential response biases in the bisection procedure, they pose a problem for the use of bisection techniques in animal psychophysics.

In the experiments reported here, brightness scales were obtained from pigeons using nonmetric scaling techniques. Pigeons were required to discriminate between *identical* and *different* pairs of lights in a *same/different* signal-detection task with a symmetrical payoff matrix. If the two lights projected onto the field directly behind the center response key were identical, the pigeon was reinforced for a single peck on the left response key. If the two lights differed in intensity, right-key pecks were reinforced. A reasonable expectation in experiments of this sort is that the accuracy with which two lights are discriminated depends on how much they differ in brightness. Therefore, the accuracy of this discrimination with respect to a given pair of lights was taken to be an ordinal measure of the perceived brightness difference between them. Specifically, if the difference in perceived brightness were greater for light pair (x,y) than for pair (w,z) , the accuracy of discrimination presumably would be greater for pair (x,y) than for pair (w,z) . Thus, I assumed that discrimination accuracy would be *monotonic* with brightness difference.

If brightness is a unidimensional sensory experience for the pigeon, one should be able to represent the brightness of each light as a point on a line segment for which the distance between any two points represents the brightness difference between the corresponding two lights. Shepard (1966) showed that there is sufficient information in the rank order of interpoint distances to determine the location of the points along the line segment up to an expansion or translation along the line segment. (For a graphical explanation of why this is true, see Schneider, 1982, pp. 323-324.) In other words, from the rank order of brightness differences, projection values, P , can be determined for the lights along a line segment, such that these projection values are linearly related to brightness,

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that is, $P = aB + c$. In this way, one can determine an interval scale of brightness for the pigeon.

Brightness scales were determined for pigeons under two conditions. In Experiment 1, the two semicircles of light to be compared were projected onto the two halves of a large bipartite field, which were separated by a 1-mm black line. The stimulus remained on until the pigeon pecked the center key. Because the two stimuli to be discriminated were separated by only a 1-mm black line, brightness contrast might be expected to affect performance. Because the stimuli remained on until the center key was pecked, the eye could easily have become adapted to the test stimuli. Thus, brightness contrast and adaptation were likely to contribute to any brightness function obtained in Experiment 1.

In Experiments 2 and 3, exposure to the test stimuli was limited. The pigeons were trained to peck the center key to produce a brief exposure ($\frac{2}{3}$ sec) to the two stimuli. The two stimuli to be compared consisted of two circles of light 4 mm in diameter separated by a distance of 15 mm. Again, the pigeon had to peck the center key to produce the stimuli. With the beak of the pigeon in contact with the key, the two stimuli subtended about 4.5° of arc, with centers separated by 17° of arc. Thus, in these two experiments, adaptation was controlled and contrast was minimized.

METHOD

Subjects

In Experiment 1, the subjects were 6 White Carneaux pigeons from the Palmetto Pigeon Plant, Sumpter, South Carolina. All had previously been trained in a saturation discrimination experiment (Schneider, 1981) and were experienced observers. They were tested 5 days per week. The subjects in Experiments 2 and 3 consisted of one of the birds in Experiment 1 plus 6 additional birds. The subjects in Experiments 2 and 3 were tested 5 days per week. On the first day of each week, however, they were presented with the most extreme pair of lights (the easiest pair to discriminate). Performance on these days was not considered in the data analysis. All birds were fed enough grain after each session to maintain them at 85% of their ad-lib weights. A vitamin supplement was added to their water once a week.

Apparatus

Experimental chamber. The pigeon's compartment ($31 \times 31 \times 32$ cm) was constructed of plywood on five sides and had a wire-mesh grid on the floor. An aluminum panel separated the subject's compartment from the stimulus and food-delivery devices. Three Lehigh Valley response keys were centered behind three 2.54-cm holes in this panel. All three response keys were positioned 22 cm above the floor of the chamber. The middle response key was centered on the panel, and the two side keys were placed 7.5 cm from the center of the panel. Each side key could be illuminated by a GE 1829 28-W bulb with a Kodak Wratten 80B filter and Kodak Wratten neutral-density filters to shift its color temperature above $4,000^\circ$ K and to adjust its luminance. In Experiment 1, the luminance of the side keys was set to 9.2 nt (as measured by an SEI photometer). In Experiments 2 and 3, the luminance of the side keys was reduced to 1.1 nt.

A hopper filled with mixed grain could be made available through a 6.2×5.2 cm opening in the panel, 16 cm below the center key. The reinforcer was 3 sec access to the grain. During the reinforce-

ment cycle, the hopper was illuminated by a GE 1829 bulb with an 80B filter.

Seven GE 1829 bulbs, with 80B filters, were mounted behind a 12×11.5 cm piece of ground glass on the ceiling of the chamber. In Experiment 1, this light remained on for the entire session, except during presentations of the test stimuli. The average luminance of this light in Experiment 1, as measured by an SEI photometer, was 58.9 nt. In Experiments 2 and 3, this light was used to provide sufficient illumination to enable the pigeons to locate the center key at the beginning of the trial. At its brightest point it measured 1.2 nt. It was illuminated only to signal the onset of a trial and was terminated with a peck on the center key.

Optical system. Stimuli were projected onto a piece of frosted glass (mounted directly behind the center response key) using the projection system shown in Figure 1. The light source (0) for both channels was a voltage-regulated 500-W tungsten-halogen lamp with a color temperature of $3,000^\circ$ K. Two beams of light from the source were used to form the two fields. In each beam channel, light from the source passed through heat-absorbing glass (1) and a collimating lens (2). A field stop (3) was inserted at this point. In Experiment 1, the field stop blocked half of the beam so that a semicircle was projected on each half of the stimulus field (10). In Experiments 2 and 3, a circular field stop was introduced, such that a small circular field 4 mm in diameter was projected on each half of the stimulus field. After reflecting off a right-angle prism (4), the collimated light passed through a filter box (5) containing blocking and neutral-density filters. After passing through the second lens (6), the beams from the two channels combined by passing through

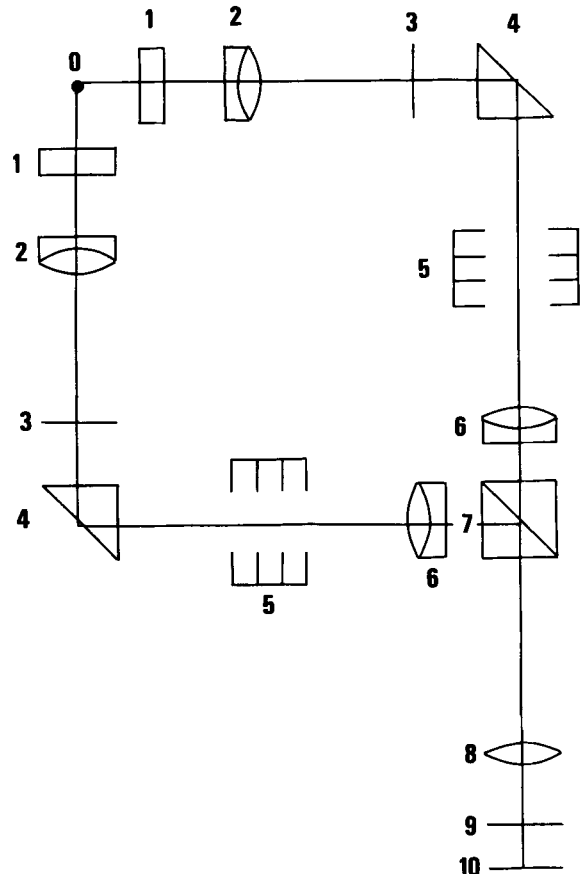


Figure 1. Schematic diagram of the optical system employed.

a beam splitter (7). A final lens (8) was used to complete the projection system and to image the field stop on the ground-glass projection field (10), which was located 1 cm behind the response key. In Experiment 1, an opaque black line divided the projection field down the center (width = 1 mm). Each edge of the bipartite field was focused on this black line. This, combined with a circular field stop (9), 27 mm in diameter, provided two semicircular fields of light, each with a radius of 13.5 mm, separated by 1 mm.

In Experiments 2 and 3, an opaque field stop with two 4-mm diameter openings, whose centers were separated by 15 mm, replaced the circular field stop (9) from Experiment 1. The circular image provided by the field stop at (3) was focused on these openings. Thus, in Experiments 2 and 3, two 4-mm diameter circular fields of light with center-to-center separations of 15 mm appeared on the projection field (10). In all three experiments, stimulus presentation was controlled by a shutter interposed in the final optical pathway.

Motors attached to the filter boxes interposed the neutral-density filters programmed for a particular trial. The color temperature of the light was adjusted upward using 80B filters in the two channels. The heat-absorbing glass eliminated the infrared mode of energy. A Kodak Wratten 2A filter was also inserted into the channels to eliminate the ultraviolet portion of the spectrum (see Wright, 1972a). The intensities of the lights in both channels were controlled by inserting Ealing neutral-density filters in the optical channels by means of the motor-driven filter changer.

Stimulus calibrations. The spectral transmittances of the heat-absorbing glasses, the interference filters, and the 2A and 80B filters were determined using a Unicam SP 1800 spectrophotometer. The correlated color temperature of the light was computed in the following manner. First, the spectral radiance of a black body radiator with a color temperature of 3,000° K (the color temperature of the bulb) was adjusted by the transmittances of the nonneutral optical components in the channel (the heat-absorbing glass, and the 2A and 80B filters). Second, the correlated color temperature was computed from the adjusted spectrum. The correlated color temperature of the white light was 5,400° K with chromaticity coordinates $x = .335$ and $y = .370$. The unfiltered luminance of this white stimulus was 243 nt in Experiment 1. In Experiments 2 and 3, the luminance of the white light was reduced to 38 nt by interposing additional neutral-density filters.

The intensity of the stimulus was controlled by interposing neutral-density filters in the optical channel. The 10 stimuli employed in Experiment 1 differed from the reference luminance of 240 nt by $-1.52, -1.26, -.98, -.82, -.69, -.61, -.48, -.26, -.12,$ and 0.00 log units. The 10 stimuli employed in Experiments 2 and 3 differed from the reference luminance of 38 nt by $-2.52, -2.24, -2.08, -1.74, -1.38, -.98, -.82, -.48, -.26,$ and 0.00 log units.

Procedure

Final procedure: Experiment 1. Prior to the beginning of a session, each pigeon was left in the darkened chamber for 2 min. At the beginning of a trial, the bipartite field was presented. The side keys were dark. A single response on the center key illuminated the side keys. The stimulus pair remained on until one of the side keys was pecked. If the two halves of the stimulus field were identical in intensity, a response to the left side key was designated as correct. If the two halves of the field differed in intensity, a response on the right side key was designated as correct. Access to food for 3 sec followed 20% of the correct (right or left) responses. The other 80% were followed by .25-sec access to food. The latter time period was too brief for the pigeon to eat any grain. It simply served as feedback for correct responses. Incorrect responses (responding left for different, or right for identical intensities) produced an intertrial period. In all cases, time between a side-key response and the beginning of the next trial was 6 sec. Key lights and stimuli were terminated when a response to a lighted side key occurred. The adaptation light was turned on during the intertrial period.

This procedure is equivalent to a same/different signal-detection paradigm with a symmetrical payoff matrix. Only a single pair of stimuli was employed per daily session. The four possible stimulus combinations appeared during a session with equal frequency: (1) Stimulus i on both halves of the field, (2) Stimulus j on both halves of the field, (3) Stimulus i on the left and Stimulus j on the right, and (4) Stimulus j on the left and Stimulus i on the right. Each session consisted of 240 trials. Since the payoff matrix was constant throughout the experiment, response bias should have remained constant. Thus the percentage of correct responses should be monotonically related to d' or any other measure of discriminability.

Each pigeon experienced all possible pairs of 10 stimuli. Only one pair was presented per daily session.

Final procedure: Experiment 2. In Experiment 2, the overhead light was turned on at the beginning of a trial to enable the bird to locate the center key. A single peck on the center key produced a $\frac{2}{3}$ -sec presentation of the stimulus pair and extinguished the overhead light. At the end of stimulus presentation the two side keys were illuminated. The luminance of the two side-key lights was the same as that of the bright portions of the overhead signal light.

Reinforcement conditions and intertrial times were the same as in Experiment 1. The overhead light was turned off during the intertrial period. The overhead signal light and the side-key lights served to maintain the pigeons in a constant state of light adaptation. In all three experiments the value of the adapting stimulus was close to the logarithmic midpoint of the intensity extremes employed in the experiments.

Preliminary training. The 6 birds in Experiment 1 were the same 6 used earlier to scale saturation (Schneider, 1981). They were switched to intensity discrimination and run for several months on many intensity pairs before Experiment 1 was initiated. One of these birds continued into Experiments 2 and 3. It is interesting that when these birds were first transferred to the brightness-discrimination paradigm, performance was at or near chance level. A considerable training period was required before they again performed at acceptable levels. It appears, then, that the pigeons, when faced with a new stimulus domain, had to relearn the same/different concept for this new dimension. The long time period required for such training indicates that it is a difficult concept to acquire and that it does not transfer readily from one domain to another.

For Experiments 2 and 3, 6 new birds were trained according to the procedure used previously (Schneider, 1972) until they could perform with greater than 90% accuracy on the most disparate pair of stimuli employed in Experiment 1. At that point, they were switched to the procedure employed in Experiment 2, but the stimuli were left as two semicircles. Stimulus presentation time, however, was initially 2 sec long. When discrimination accuracy exceeded 90% at this duration, stimulus duration was decreased progressively until a $\frac{1}{3}$ -sec level was reached. The shapes of the two stimuli were then changed from the semicircles used in Experiment 2 to 10-mm circles whose centers were separated by 15 mm. After performance had stabilized for circles of this size, their diameters were gradually reduced to the 4-mm value used in Experiments 2 and 3. As the diameters of the circles were reduced, we found that an increase in stimulus duration was needed to maintain an adequate level of performance. Stimulus duration was increased to $\frac{2}{3}$ sec in Experiments 2 and 3. It took about 1½ years to train the birds in this procedure.

RESULTS

Experiment 1

In Experiment 1, each of the 6 pigeons experienced every possible pair of 10 light intensities. The accuracy of discrimination (number of correct choices ÷ number of trials) was then computed for every pair. These dis-

crimination scores were then used to determine a rank order of brightness difference for each pigeon. Kendall's coefficient of concordance (W), which measures the extent of ordinal agreement across pigeons, was .849, indicating good agreement.

The rank order, averaged across subjects, was then used as an input to a nonmetric scaling program (Carvellas & Schneider, 1972). This program determines the best one-dimensional representation for the 10 stimuli, based on the rank order of the brightness difference measures. Stress, Kruskal's (1964) measure of goodness of fit, for this configuration was 8.1%.

To evaluate how closely this one-dimensional representation approximated an interval scale of brightness, the index of metric recovery (M) was estimated from Young's (1970) nomogram. M is the squared Pearson correlation coefficient between the true distances (whose rank ordering serves as the input to the algorithm) and the distances produced by the algorithm. Hence, M varies between 0 and 1, and $M=1$ means that the true distances have been perfectly reconstructed. In no empirical investigation using these techniques are the true distances known, but Young (1970) provided a nomogram for estimating M from the number of points, number of dimensions, and stress—all of which are available. The result is that, if M is sufficiently high (e.g., above .98), the point coordinates produced by the algorithm are properly regarded as an interval-scale representation for the original points. In the present case, M was estimated to be .98. Hence, the projection values obtained from the program may be taken as an interval scale of the brightness of the 10 intensities.

Figure 2 shows a plot of the brightness values as a function of log relative intensity. A linear function provides a good fit to the data. Attempts to fit a power function to these points resulted in an exponent near 0. (As the exponent of a power function approaches 0, the power

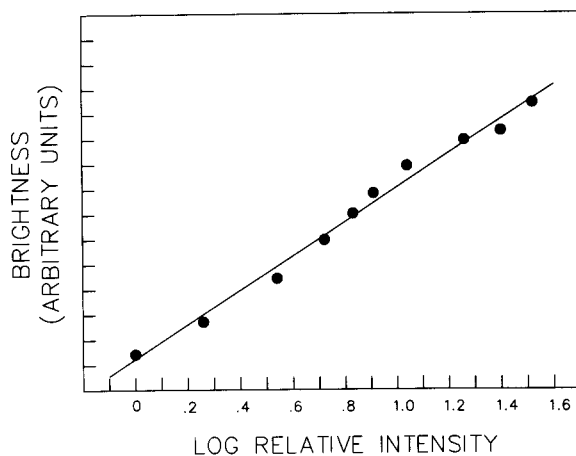


Figure 2. Brightness values as a function of log relative intensity for Experiment 1. The luminance of the most intense stimulus was 240 nt.

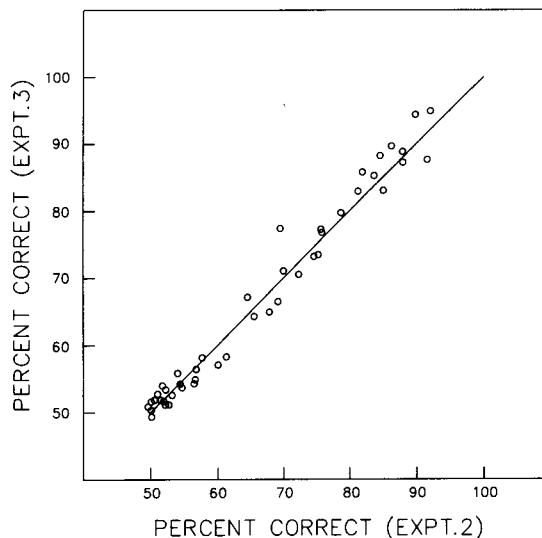


Figure 3. Discrimination accuracy scores for stimulus pairs in Experiment 3 as a function of the corresponding discrimination accuracy scores in Experiment 2.

function increasingly resembles a log function.) Thus, brightness in this experiment conforms to Fechner's logarithmic law rather than Stevens's power law.

Experiments 2 and 3

In Experiments 2 and 3, to control for adaptation effects, a peck to the center key produced a $\frac{2}{3}$ -sec exposure to a stimulus pair comprising 4-mm circles with center-to-center separations of 15 mm to reduce contrast. With the pigeon's beak in contact with the key, the circles each subtended about 4.5° of arc, and their centers were separated by 17° of arc. The stimulus intensity range was also increased to 2.52 log units. Experiment 3 was a replication of Experiment 2.

For the 7 birds in Experiment 2, $W=.88$, and for the same 7 birds in Experiment 3, $W=.86$, indicating good agreement across subjects. For each experiment, the ranks of the brightness difference measures were averaged across subjects to obtain an average rank order of brightness difference for each experiment. The Spearman rank-order correlation coefficient (r_s) between the average rank for a stimulus pair in Experiment 3 versus the average rank for the same pair in Experiment 2 was .98. Figure 3 plots discrimination accuracy, averaged over birds, for each stimulus pair in Experiment 3 against the corresponding value in Experiment 2. The figure shows good agreement across the two experiments. Both the r_s value and Figure 3 indicate that the results of Experiment 3 replicated those of Experiment 2. Accordingly, the ranks of the stimulus pairs were averaged across subjects and experiments, and this average rank order of the 45 pairs served as input to the nonmetric scaling program.

Figure 4 plots the projection values obtained from the nonmetric scaling program as a function of log relative intensity. Stress was 1.2%, which indicates an index of

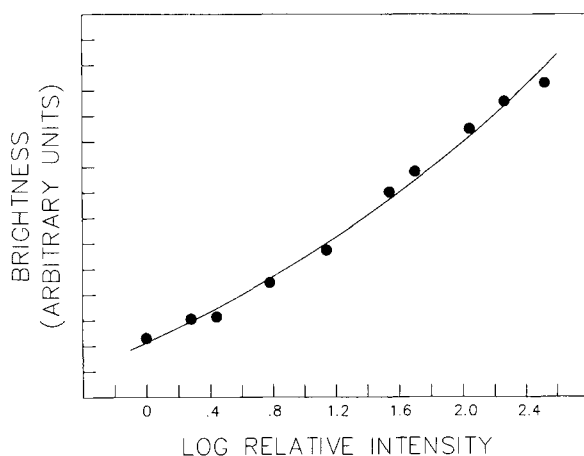


Figure 4. Brightness values as a function of log relative intensity for the data from Experiments 2 and 3. The luminance of the most intense stimulus was 38 nt. The smooth curve is a power function with an exponent of 0.13.

metric recovery well above .99. With the exception of the highest intensity value, the points in Figure 4 exhibit the positive acceleration associated with a power function in these coordinates. The smooth curve fit to the data points is the best-fitting power function; the value of the exponent is .13.

DISCUSSION

Figure 2 shows that the brightness values obtained in Experiment 1 are best described as a logarithmic function of stimulus intensity. In this experiment, the stimuli were presented at the beginning of a trial and remained on until the pigeon pecked the side keys. A significant delay between the onset of the stimulus and a peck to the key would adapt the eye to the test stimulus. As Green (1962) pointed out, when the eye is adapted to the stimulus light, brightness should be approximately logarithmic with stimulus intensity. This is exactly what Figure 2 shows.

A complicating factor in Experiment 1 was that the two semicircles were separated by only 1 mm, a situation in which stimulus contrast can influence perceived brightness difference. Although there have been a number of studies on the effects of contrast on brightness judgments in humans, I know of no studies of the effects of contrast on brightness difference judgments. Therefore, it is difficult to speculate how this factor might have affected perceived brightness difference in this experiment.

In Experiments 2 and 3, the stimuli in a pair were far apart and brief, therefore interactions between the two lights and adaptation effects are likely to be negligible. The brightness values obtained from these two experiments indicate that brightness can be described as a power function of intensity with an exponent of about .13. Although a power function provides a better fit than does a logarithmic function in that it accounts for more of the

total variance (.993 as opposed to .987), both provide a reasonably good fit to the data. It is difficult to discriminate between them because log functions and power functions with low exponents do not differ extensively over a 2.5-log-unit range. Although it may be difficult to argue strongly for one function over the other, it is, nevertheless, true that the brightness scale obtained here is consistent with a power-function representation. In fact, the exponent of .13, even though it is about half the value obtained in magnitude-estimation experiments on brightness in humans, agrees well with the results of Curtis (1970), in which humans judged brightness differences over a similar range of stimulus intensities: Curtis reported brightness exponents of .15 and .112, respectively, for magnitude and category estimates of brightness difference. Thus, the brightness function obtained in this experiment with pigeons agrees well with that observed in humans. What is interesting is that in both cases, where brightness-difference measures were involved, the brightness scales so far uncovered had exponents that were about half those found in magnitude-estimation experiments. Similar results have been found for the relation between human loudness and loudness-difference judgments and may be a general feature of sensory processing mechanisms (Marks, 1979).

The present study provides a means of constructing a scale for a psychological attribute of a light stimulus that is based on relatively weak assumptions about the subjects' responses. We need only assume that discrimination accuracy is monotonic with brightness difference. Although it is always possible to conceive of models of brightness discrimination that might violate this assumption (particularly those in which brightness variability changes extensively and erratically with stimulus level), this assumption remains one of the weakest in the animal scaling literature and is quite likely to be satisfied in practice. In general, the weaker the assumptions are in a scaling technique, the more likely a scale obtained via this technique is free of distortions that biases might produce. To the extent that the brightness scale obtained in the present experiment is free of such biases, it describes how differences in intensity are coded by the visual system of the pigeon.

Nonmetric techniques have also been used to determine sensory representations for hue and saturation in the pigeon. Schneider (1972), using equivalent nonmetric-scaling procedures, constructed a color circle to represent the pigeon's perception of hue, and showed that the spacing of wavelengths along the perimeter of this color circle was consistent with wavelength discrimination data in pigeons (Wright, 1972b), and with wavelength generalization data in pigeons (e.g., Blough, 1961; Guttman & Kalish, 1956; Shepard, 1965; Wright & Cumming, 1971). Schneider (1981) used these same nonmetric techniques to construct a scale of saturation for a 630-nm light. In that experiment, perceived saturation was a linear function of colorimetric purity. A linear function between perceived saturation and colorimetric purity was also found

(100 msec) or a "short" (50 msec) duration and whether it contained the target letter "F." No effect of display size on judged duration was observed when both tasks were performed simultaneously. It is therefore not clear from the work of Thomas and his colleagues whether concurrent processing is likely to have no effect or to produce an increase or decrease in judged duration.

These diverging results are possibly due to the specific conditions under which concurrent processing was studied by Thomas and his coworkers. For instance, the very short durations they used, usually less than 100 msec, make it difficult to assume that their subjects were effectively sharing attention between timing and the processing of some other stimulus characteristic. Actually, Long and Beaton (1980a, 1980b) showed that in Thomas and Weaver's (1975) experimental task, subjects could assess stimulus duration through visual persistence without having to call for a timing process.

Thus, although many studies agree that attention and time estimation are closely related, the precise form of the interaction seems to be determined by the specific experimental conditions assumed to control attentional demands. Since it is doubtful that attentional timesharing can be effectively manipulated under very short durations (under 100 msec), we might gain a better insight into the relationship between attention and subjective duration by having subjects estimate longer time intervals in the presence of nontemporal processing, somewhat along the line of Hicks and his colleagues (Hicks et al., 1977; Hicks et al., 1976). This approach is further supported by studies in which subjects are requested to fingertap at a rate of one tap per 2 subjective seconds while simultaneously performing some other cognitive processing. In Vroom (1973, Experiment 1) subjects tapped continuously until the occurrence of an auditory stimulus, which was present every 10 sec. The subjects were to react as rapidly as possible to the stimulus. Just before stimulus presentation, there was a considerable slowdown in the tapping rate.

In a somewhat similar procedure, Rousseau, Picard, and Pitre (1984) had subjects produce discrete 2-sec intervals. Between 400 and 700 msec after the onset of the interval, a 10-msec tone occurred. The frequency (high or low) of the tone had to be discriminated. When subjects judged that 2 sec had elapsed since the first tap, they terminated the interval by depressing one of two pushbuttons, depending on the frequency of the tone; the discrimination response was postponed until the end of the interval and was combined with the fingertap that marked the end. Produced duration was shown to increase linearly with the length of the delay between the onset of the interval and the tone. It is important to note that overproduction (i.e., lengthening) in Vroom's (1973) and Rousseau et al.'s (1984) tapping situations, corresponds to an underestimation in verbal estimation tasks such as that used by Hicks et al. (1976).

The production method appears particularly interesting because this procedure makes it less likely that judged time

is merely a by-product of perceptual processing that is triggered by a stimulus. In both cases, the production performance is linked to changes in the processing of a nontemporal stimulus. The tapping experiments demonstrated that this particular task can be an efficient means for studying the relationship between attention and judged time. Unfortunately, neither of these studies specifically proposed a way to systematically manipulate attention. This leaves some basic questions unanswered. What type of cognitive processing interacts with estimated time? How is time shared between temporal and nontemporal processing?

A psychophysical model¹ proposed by Rousseau et al. (1984) suggests a systematic approach to the problem. The model proposes that subjects produce an interval by accumulating, after the first tap, a criterion number of pulses emitted by an internal source. The pulses are gated from the emitter through an attentional gate that enables pulse accumulation when it is in an on state. Concurrent cognitive processing that requires attention will put the gate in an off state, thus preventing pulse accumulation. Compared with a situation in which a subject has to produce only time intervals, additional time will be required to reach the criterion number of pulses if time sharing occurs between timing and some other nontemporal processing. This will lead to a lengthening of the produced interval, equal to the total duration of time off.

The present paper describes an attempt to test some of these propositions about the time sharing between concurrent nontemporal and temporal processing. Nontemporal processing demands were manipulated in a memory search (MS) task that was developed by Sternberg (1966). In an MS task, the subject is shown a set of alphanumeric elements, the positive set, and after a short delay is shown a target element, the test item, which is to be recognized as a member or a nonmember of the positive set. Sternberg reported recognition reaction time (RT) to increase linearly with positive-set size. Furthermore, the RT functions had identical slopes, about 35 msec, whether the test item was in the positive set (positive trial) or not (negative trial). These results were interpreted as showing MS to be performed through an exhaustive series of mental comparisons between the test item and the positive-set items, comparisons whose durations were independent and additive.

These features of the MS task enable specific predictions to be made about its effect on a concurrent timing process. Assuming that MS and interval production interact according to a kind of preemptive timesharing (Schweickert & Boggs, 1984) as described by the Rousseau et al. (1984) model, interruption in the timing process by concurrent MS should cause a lengthening in the produced interval that is proportional to the number of mental operations performed in the search and equal to their total duration.

The paradigm designed for the present experiment combined temporal production and MS. The subject was asked

to produce a 2-sec temporal interval by fingertapping, and the MS was interpolated in the temporal production in the following way. The positive set was memorized before the beginning of the temporal production. Then, 500 msec after the first tap, a test item was presented. The subject terminated the 2-sec interval by depressing one of two pushbuttons, depending on whether the test item did or did not belong to the positive set. The main cognitive operations performed while duration was being estimated were assumed to be the identification of the test stimulus, the comparison of this stimulus with each of the positive-set items, and the decision about the occurrence of a match during the comparison stage.

The basic hypothesis of the present experiment was that memory load, as defined by positive-set size, should have the same effect on temporal productions as it has on reaction time. The duration of the temporal productions should increase linearly with the number of elements in the positive set. The slope of the function should have a value equivalent to that of the RT function, which would reflect the comparison time.

METHOD

Subjects

Ten subjects were paid \$5 per session for their participation. They were young adults who had a mean age of 25 and who were naive to the experimental task.

Apparatus

The experiment was run in a sound-attenuated test chamber. The subject was seated, with his/her head in a frame that could be fitted at the chin and forehead levels. The subject's right arm rested on a table from which protruded three pushbuttons; when the test stimulus appeared, a positive or a negative response was made by pushing the right or the left button, respectively. A Tektronix Model 602 screen on which the stimuli were presented was about 80 cm from the subject's eyes. Roughly 10 cm below the screen, a neon bulb (NE-40) signaled the beginning of a trial in the practice sessions. The positive-set presentation marked the trial's beginning in the experimental sessions. Approximately 15 cm above the screen was a row of three small lamps which conveyed feedback for the temporal-production task. Accuracy feedback on the detection task was provided through headphones (Realistic PROIIA).

Procedure

After an introductory session in which the experiment was explained to the subjects, there were four practice and two experimental sessions.

Practice sessions. The first four sessions were designed to stabilize temporal productions and to allow the subject to practice the production and item-detection dual task. These sessions included five blocks. In the first, the subject produced 2-sec intervals. In succeeding blocks, the subject produced the same intervals while simultaneously performing a visual detection task. The trials were run as follows. The subject started the interval by depressing the middle pushbutton. During the interval, a C-shaped stimulus was displayed in the upper or the lower part of the screen; depending on the stimulus location, the subject terminated the temporal production by depressing the right or the left pushbutton, respectively. In the first four blocks of the practice sessions, accuracy feedback on the temporal productions was provided to the subject. The visual signals located above the screen informed the subject that the in-

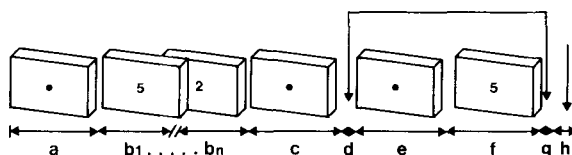


Figure 1. Example of a positive trial: (a) Fixation dot (500 msec); (b) presentation of positive set (1.2 sec per item); (c) fixation dot, which stays on until (d) subject begins the interval; (e) fixation dot (500 msec); (f) test item, displayed until (g) the end of the temporal production; (h) auditory feedback.

terval had been over, under, or within a 200-msec window centered on the 2-sec standard.

In the last block of the practice sessions, the subjects had to produce the same time interval, terminating the production according to the position of the C-shaped stimulus. In this fifth block, however, no feedback on temporal production was provided.

There were 45 trials per block with a 30-sec break between blocks.

Experimental sessions. The two experimental sessions were composed of two types of blocks. In the first block of each session, the subject carried out temporal productions combined with a simple visual detection, as had been done in the practice sessions, with feedback on his/her temporal-production performance. The aim of this block was to reset the productions around the target duration. In the next four blocks, the subject performed the experimental task: temporal productions and MS search in a dual-task situation. The MS task, similar to Sternberg's (1966) original version of the MS paradigm, was interpolated in the time-interval production in the following way.

A trial is illustrated in Figure 1. After a central fixation-dot presentation, the positive-set items were successively displayed in the center of the screen. In a positive set, a given item never occurred more than once. The items were presented in a random order for 1.2 sec each without any delay between presentations. The positive set differed from one trial to another in a varied-set procedure. After the last item, the fixation point appeared anew and remained until the subject started the temporal production by depressing the middle pushbutton. The test item was displayed 500 msec after the first buttonpress. The subject's response as to whether the test item did or did not belong to the positive set was withheld until the end of the estimated interval. If the test item was a positive-set member, the subject terminated the interval with a right buttonpress (positive response trial); if the test item was not a positive-set member, the subject terminated the interval with a left buttonpress (negative response trial). After the temporal production, an auditory signal sounded if the trial was positive. The relative frequency of positive and negative trials was equal within a block.

The set of items used in the experiment was composed of 10 different digits (0, 1, . . . , 9). The number of items in the positive set varied from 1 to 6. As was done in the practice sessions, an auditory signal was presented at the beginning and end of each block. A 30-sec break occurred between blocks. In these experimental sessions, there were 45 trials in the first block and 36 in each of the other four blocks, with 24 trials per positive-set size per subject.

RESULTS

In the practice sessions, the mean temporal intervals were 1,996 msec in the with-feedback blocks and 2,100 msec in the last without-feedback blocks. In experimental sessions, the mean interval was 2,017 msec for the first block of temporal production alone with feedback.

An analysis of variance (RBF-6,2,2; Kirk, 1982) was run on the experimental data, that is, for the temporal intervals produced without feedback during the search. Positive-set size, positive-negative trials, and sessions were the main factors. The data from all trials were included in the analysis, since error rates in MS performance were generally quite low, around 1%. Moreover, they were not related to positive-set size or to positive or negative trials.

The results showed the main effect of session successiveness to be significant [$F(1,924) = 96.5, p < .0001$]. From the first to the second session, there was a general decrease in mean productions. The productions averaged over all set sizes and response types (positive and negative) show a decrease of 105 msec. This main effect is independent of the positive-set size and trial type. The interactions between session successiveness and positive-set size [$F(5,924) = 0.73, p = .60$] and between session and positive-negative trials [$F(1,924) = 0.04, p = .85$] were nonsignificant. Therefore, in spite of between-sessions differences, the absence of an interaction with the other factors makes it possible to average over sessions.

The results further showed a significant main effect of positive-negative response trials [$F(1,924) = 18.6, p < .0001$]. The negative-trial productions were found to average 46.1 msec longer than positive-trial productions. Finally, a significant main effect of positive-set size [$F(5,924) = 11.4, p < .0001$] was found.

Since significant differences between subjects [$F(9,924) = 196.72, p < .0001$] are explained by differences in mean tapping rate, group data are still meaningful although the positive-set size effect was minimal for 2 subjects.

Figure 2 shows the temporal productions averaged over subjects and over the two experimental sessions plotted against positive-set size. Each point represents 240 observations. It can readily be seen that mean productions increased with positive-set size.

While negative trials displayed a very regular linear trend, the positive-trial function reveals some nonlinear-

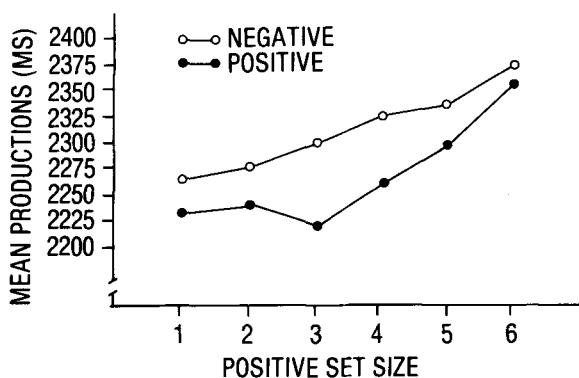


Figure 2. Mean temporal production as a function of positive-set size.

Table 1
Linear Regressions of Mean Productions as a Function of Positive-Set Size on Positive and Negative Trials

	Slope	Intercept	r^2
Positive trials	23.6	2186	.76
Negative trials	21.3	2240	.97

ity. Linear regressions, shown in Table 1, account for 97.3% and 76.0% of the variance of the mean productions on negative and positive trials, respectively.

The production functions for positive and negative trials have approximately the same slope values: they present a 1:1.1 ratio.

DISCUSSION

The aim of the present experiment was to test the effect of concurrent cognitive processing on time-interval production. It was proposed that if an MS task was interpolated within a temporal-production task, mean temporal-production functions should display features comparable to those commonly reported with RT functions under similar search conditions. Mean production should be a linear function of positive-set size with equal slopes for positive and negative responses.

In a classical item-recognition task, RT functions are known to be linear with a very stable slope, across experiments, of around 35 msec (Sternberg, 1975). This is generally interpreted as an estimate of the time needed to compare the test item with an element of the positive set. In the present task, the slope of the temporal-production function is about 23 msec. There are basically two ways to account for this discrepancy.

First, the discrepancy might be linked to differences among subjects. An examination of the individual data shows that, although the pattern of performance for the majority of our subjects follows closely the trend of the average data, temporal productions for 2 subjects are little affected by the concurrent search. Some subjects could have used different timesharing strategies (Pew, 1979). They also may have used completely opposite strategies in the memory-comparison tasks, somewhat in the line of Cooper's (1982) observations with visual search.

The reduced slope may also reflect a much more fundamental characteristic of the timesharing operations. In the Rousseau et al. (1984) model, gating is assumed to be an all-or-none process, such that accumulation of temporal information is completely interrupted by concurrent cognitive processing. Consequently, a one-to-one relationship between cognitive-processing duration and the increase in temporal production was hypothesized. However, if gating were not all-or-none, some temporal information could be accumulated concurrently with search-process execution, and only a certain fraction of the search-process duration would have to be recovered for accumulation purposes. Thus, function relating mean temporal-production duration with positive-set size should display a lower slope.

The second basic finding is that mean temporal productions were 46 msec longer when the subject reached a negative decision in the search. This result was somewhat unexpected since in the version of the item-recognition paradigm used in the present experiment, RT did not vary with response type (Sternberg, 1966). However, this increase is by no means unique in item-recognition data. With stimuli such as face photographs and nonsense forms, increases of 30 and 55 msec, respectively, have been observed in negative-trial RTs (Sternberg, 1969b). Sternberg (1969a) also reported that when the relative frequencies of positive-negative trials were varied, the average negative responses were 45 msec slower than positive responses. Otherwise, in a fixed-set procedure (i.e., when the positive set does not vary from trial to trial), in which positive and negative responses are equiprobable, positive responses were produced 40 msec faster than negative responses, at each set size (Sternberg, 1975).

The present dual task and the fixed-set procedure share one important feature: compared with the RT varied-set procedure, they impose less constraint on the subject. Here, the observed increase in temporal productions could reflect a negative decision duration which, in other more demanding circumstances, might be compressible.

Finally, mean temporal productions did vary significantly over sessions. There was a general decrease in mean production duration from the first to the second session, which could be interpreted as a practice effect. However, the effect of the load as defined by the increase in temporal-production duration in proportion to positive-set size persisted in spite of practice, as indicated by the fact that the variable session showed an insignificant interaction with set size. The reduction in overall load effect of MS on mean time-interval production over sessions is consonant with other findings. Extensive practice of the item-recognition task reduced general mean RT without altering the slope of the function (Kristofferson, 1972).

It should be noted that it is relatively unimportant here that subjects tap at different mean rates, as is the case with the mean RT of subjects in the item-recognition task. The basic interest of the experiment lies in the within-subject or within-group effect on temporal production of load variation in the MS.

The results suggest that the two tasks, temporal production and memory search, interact in a particular way. The somewhat surprising similarity in the overall features of the time-production data and the RT data brings some justification to the a posteriori interpretations that have been proposed. The time-interval-production task may be used as an index of the cognitive operations involved in MS when they are performed concurrently. This dual task appears particularly interesting because it allows the investigation of processes that are usually studied with RT to be examined in new conditions without great time pressure. Moreover, the paradigm developed here does appear to provide a systematic means for studying the interaction between cognitive processing and time

estimation. The present data, if interpreted within the context of timesharing, require the identification of the mental resource or function shared by temporal and nontemporal processing. One likely candidate might well be the working memory.

Unfortunately, the exact replication of Sternberg's (1966) search conditions led to a logical difficulty for the assumption that timing and memory search are performed concurrently, since, in Sternberg's study, the test item remained visible until the subject made the buttonpress response. Therefore, there was no need for the subject to process the probe as soon as it was presented.

It would be logically possible, then, to consider the data as the result of a successive execution of the two tasks: the subject completes the timing, and then encodes the test item to perform the search. This could account for the results without the need to infer additive interference caused by the timesharing of a common cognitive process.

A simple evaluation of this possibility could be performed by assuming that the total intertap duration, when positive-set size = 1, is the sum of the mean production alone without feedback, with the average RT reported by Sternberg (1966) at $n=1$. In the present experiment, the mean temporal production without feedback and without search (i.e., last block of the practice sessions) was 2,100 msec. Moreover, Sternberg showed that the MS of a positive set of one item was about 438 msec for positive trials. Thus, a reasonable estimate of the total time-interval-production duration resulting from the successive execution of the two tasks is roughly 2,538 msec. The actual mean interval productions (positive trial, positive set = 1) is 2,250 msec, leaving a difference of 288-msec. This difference implies either a much shorter RT in the search task or a reduced production adjusted for the successive processing. The 288 msec difference could be reduced by assuming that input and output times are common for the two tasks; however, this still leaves an estimated 100-200-msec difference unaccounted for.

It remains difficult to reach a conclusion on the successive- versus concurrent-processing issue on the basis of the present data. Any conclusive interpretation will have to be delayed until new data are provided under a methodology that reduces the possibility of using a successive-processing strategy. An experiment in which the test item is presented briefly could make an interpretation in terms of a successive-execution strategy much less probable.

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Notice

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