

Table 1. Results of an additivity experiment. Perfect additivity would yield a value of 1.0. Two observers: RMB and PKK.

Minimum border		Equal brightness	
RMB	PKK	RMB	PKK
<i>Wavelengths 492 and 595 nm</i>			
0.975	1.030	1.419	2.012
.976	0.965	1.523	1.344
.981	1.009	1.475	1.309
1.060	1.040	1.647	1.205
1.044	1.094	1.549	1.587
0.990	1.026	1.362	1.377
<i>Means</i>			
1.004	1.027	1.500	1.472
<i>Standard deviations</i>			
0.027	0.037	0.092	0.267
<i>Wavelengths 480 and 580 nm</i>			
1.014	1.048	1.512	1.224
1.010	1.011	1.238	1.309
	0.980		1.126
	1.030		1.238
	1.063		1.100
	0.933		1.290
<i>Means</i>			
1.012	1.011	1.375	1.215
<i>Standard deviations</i>			
	0.043		0.077
<i>Wavelengths 480, 540, and 630 nm</i>			
0.925	0.961	1.160	1.392
1.028	.973		
0.969	.991		
.988	1.026		
<i>Means</i>			
0.978	0.988	1.160	1.392
<i>Standard deviations</i>			
0.038	0.025		

unity (unity defined as the radiance value for each component yielding a minimally distinct border). The observer then added light of 492 nm to this value of 595 nm to achieve minimization of border. We used proportions ranging from 10 to 90 percent of unity for the wavelength 595 nm. We should point out that border minimization of the mixture did not usually result in complete disappearance of the border as was the case in the first series of experiments. The calculations in this experiment were the same as those already described (12).

This experiment allowed us to make a series of precise predictions of the percentage of 492 nm that should be mixed with the set percentage of 595 nm (13). One can see (Fig. 2) that for both RMB and PKK the points fall close to the predicted (solid) line that defines the additivity law. The predicted line accounts for 96 percent of the variance for RMB and 92 percent of the variance for PKK.

Thus we have shown that, when the minimally distinct border criterion is used, the additivity law is obeyed for a side-by-side comparison. This finding is true whether the proportions of the

mixture lead to complete cancellation of hue (first experiment) or to only partial cancellation (third experiment). As did other experimenters we have found that the additivity law is not obeyed when equal brightness is used as a criterion (second experiment).

One implication of our results is that additivity failures in heterochromatic photometry could be avoided by use of the criterion of minimally distinct border without placement of any restrictions on the chromaticities of the fields to be compared. Whether this procedure would lead to the same spectral-sensitivity functions as does flicker photometry (which also has been shown to eliminate additivity failure (14) remains to be seen (15).

Our results also have implications for the class of experiments in which one wishes to deal with visual effects produced by chromatic differences alone. Equation of stimuli for brightness (or luminance) provides little assurance that only chromatic differences will remain: since it is probable that the achromatic components of the visual system are unequally activated, such stimuli probably will not yield minimum visual acuity, minimum contrast, or minimum electrophysiological response.

ROBERT M. BOYNTON
PETER K. KAISER

Center for Visual Science,
University of Rochester,
Rochester, New York 14627

References and Notes

1. The term V_λ does not represent the spectral sensitivity of any real eye; it is a function based upon averaged data obtained in 1923 [K. S. Gibson and E. P. T. Tyndall, *Bull. Bur. Std.* **19**, 131 (1923)]. It was sanctioned in 1924 by the 6th session of the Commission Internationale de l'Eclairage.
2. Heterochromatic photometry and Abney's law are summarized by Y. LeGrand, *Light Colour and Vision* (Wiley, New York, 1957). Although Abney's law has been repealed many times for direct brightness matching, it is true to a good approximation in the flicker-photometry method (14).
3. Helmholtz [*Physiological Optics* (Dover, New York, 1962)] mentions that Fraunhofer wrote of a minimally distinct border that could be achieved between areas of different color, but Fraunhofer was not concerned with photometric measurement.
4. In a series of experiments to be described elsewhere.
5. A two-state neural element is hypothesized for the sake of simplicity. We could hypothesize a three-state neural element as implied by DeValois's findings in the lateral geniculate nucleus of the monkey, but the mathematical statement of the model would not be altered.
6. See R. M. Boynton, *J. Opt. Soc. Amer.* **50**, 929 (1960), for an earlier discussion of some of these ideas.
7. As opposed to dark colors. At the present stage of development our model does not incorporate the effects of induction generated by stimulation by the surrounds.
8. If a three-state element were hypothesized, the model would have to be altered to allow for a given element to give rise to either of

two chromatic sensations when the element is not in a neutral state.

9. In the first two series of experiments the observers made six judgments of minimum border (or equal brightness) for each single-wavelength condition and six judgments for the mixture condition. Additivity was calculated from the mean values of these judgments. All determinations of minimum border (or equal brightness) were made by the method of adjustment.
 10. Deviations of this magnitude for complementary wavelengths have been reported by S. L. Guth, *Vision Res.* **7**, 319 (1967); R. Morrocco and S. L. Guth, before Midwestern Psychol. Assoc., May 1967; M. Tessier and M. Blottiau, *Rev. Optiques* **30**, 309 (1951).
 11. J. W. T. Walsh, *Photometry* (Dover, New York, 1958).
 12. In this experiment we used the method of adjustment. Five determinations were made at each step, and the median value was used in the calculations because, on receiving the settings for 595 nm against white, the experimenter had to calculate immediately the setting of the neutral density wedge required for a certain percentage of unity. This determination was made separately for each set of data collected.
 13. This method is similar to the test of additivity used by Tessier and Blottiau (10) with equal brightness as a criterion; they found large additivity failures.
 14. For example: H. E. Ives, *Phil. Mag. Ser. 6* **24**, 845 (1912).
 15. F. H. C. Marriott [in Davson, *The Eye* (Academic Press, New York, 1962), vol. 2, p. 241] states that different functions are obtained by the three methods (flicker, side-by-side, and step-by-step). Therefore it is reasonable to assume that the minimally distinct-border criterion may yield a still different function.
 16. Supported by NINDB grants NB00624 and 2F2 NB 12, 980-02.
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Dielectrically Heated Sensor of Water-Vapor Pressure

Abstract. Existing psychrometers of small dimensions cannot provide accurate long-term measurements of water-vapor pressure without frequent maintenance and recalibration. A small, simply constructed instrument employing dielectric heating and avoiding many of the problems of available sensors is described. The calibration curve depends only on the pressure-temperature curve for saturated lithium chloride.

Of many available hygrometric sensors, one frequently favored for micro-meteorological work is the dew cell. This device is rugged and has good short-term stability, and its range is limited only by lithium chloride triple points which correspond to water-vapor pressures of 1.3 and 30.0 mb (1). However, the dew cell is bulky and is susceptible to problems associated with the resistive dissipation of widely varying power, which rises to high levels under conditions of high vapor pressure. The conductive path is an extensive thin layer, the resistance of which may be required to vary repro-

ducibly through more than four orders of magnitude (1). Path resistance is thus very susceptible to loss and redistribution of lithium chloride, which can arise from local temperature gradients, and to surface contamination of the electrodes.

These problems can be avoided by use of dielectric heating which has two further advantages: (i) resistance considerations are no longer a dominating factor in design, so that miniaturization is easy; and (ii) the requisite coating of insulation protects electrodes from surface contamination. A small sensor incorporating these qualities has been constructed having a calibration curve in agreement with the vapor-pressure curve of a saturated solution of lithium chloride.

The sensor consists of a thick-walled nylon tube, 2 mm in outside diameter and 7 mm long, having a copper and copper-nickel thermocouple set in epoxy resin at its axis. The tube supports two capacitor "plates" consisting of bifilar windings of enameled copper wire (26 standard wire gauge) separated by absorbent tissue (Kleenex) (Fig. 1). The tissue is wet with a saturated solution of lithium chloride, and a radio-frequency (70 Mhz) voltage is applied between the two windings. This voltage is provided by very loose coupling of the sensor to a simple single-transistor radio-frequency oscillator having nominal output of 2 watts, and adjustment of the coupling so that the rise in temperature of the dry sensor is small ($< 1^\circ\text{C}$).

Wetting of the Kleenex tissue with a saturated solution at room temperature provides more water than is required at the equilibrium operating temperature; solid lithium chloride is therefore always present during operation, to ensure saturation of the solution.

For calibration in the higher vapor-pressure range, the sensor is mounted in a short length of plexiglass tubing connected to an airstream of known specific humidity—known by bubbling of the air through boiling water and then through water having a known lower temperature, and by then bringing it to a measured high temperature by passage through a coil of copper tubing. For lower vapor pressures, air is passed over solutions of sulfuric acid, and the resultant vapor pressure is measured with a differential psychrometer (2).

Thermal dissipation in still air is measured by temporary winding of a resistive heater of fine nichrome wire

on the sensor; dissipation is of the order of 0.02 watt/ $^\circ\text{C}$, so that 1 watt of power is required to maintain a 50°C temperature differential between sensor and environment—more than is required in natural environments.

The response time, defined as the time for complete restoration of equilibrium, is measured at a vapor pressure of 10.2 mb and ambient temperature of 26.5°C by turning off the power for a few seconds. The response time is 200 seconds in still air, which compares more than favorably with a typical figure of 15 minutes for the dew cell in unspecified conditions of air movement (4). Since response time

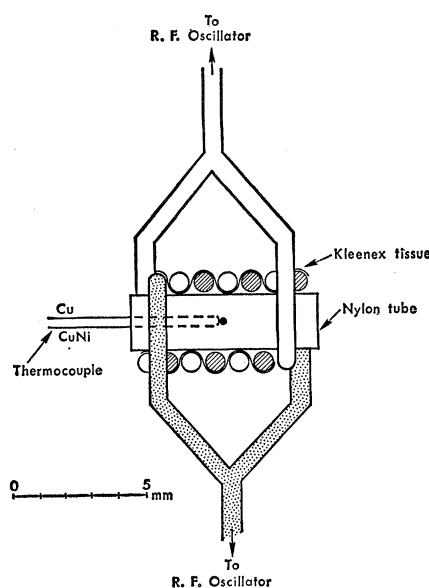


Fig. 1. Schematic diagram of dielectrically heated water-vapor sensor, showing the two windings or plates.

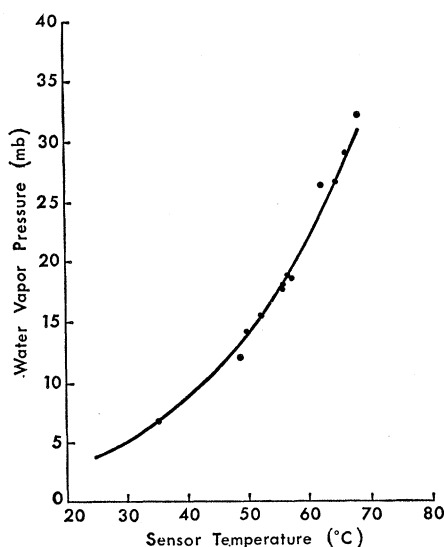


Fig. 2. Calibration of sensor: measured points and the vapor-pressure curve of saturated solution of lithium chloride.

depends strongly on rate of exchange of water vapor between sensor and atmosphere, either reduction in size of the sensor or alternative methods of supporting the lithium chloride in the electric field are expected to reduce the response time appreciably.

Never, except when the device is turned off, is there evidence of migration or loss of lithium chloride from the absorbent medium; and there is no evidence of hysteresis effects. The device can be made to oscillate by very substantial increase in the dielectric field strength.

This type of humidity sensor has two advantages: (i) its thermal efficiency (and hence its calibration stability) is less dependent on the conductivity of the solution; and (ii) the electrodes are not exposed to atmospheric oxidation or contamination, since insulated electrodes are (must be) used for avoidance of resistive heating. Such contamination is a common cause of long-term drift in calibration in other saturated-salt-solution hygrometers and can result in failure of an instrument.

Possibly the behavior of lithium chloride, with respect to the formation of hydrates, may be more predictable in a dielectrically heated sensor, and detailed study of the 1.3- and 30.0-mb points may be repaid in terms of extension of operating range. Despite the fact that air velocity past the sensor was varied considerably, and although the temperature of the calibration cabinet ranged over 10°C , there was good agreement between the calibration points of the instrument and the curve relating the saturation vapor pressure of lithium chloride to temperature (Fig. 2) (3). Thus, within the limits of our testing, calibration depends only on the properties of lithium chloride solution and is remarkably insensitive to constructional and environmental factors.

G. F. BYRNE
C. W. ROSE

*Division of Land Research,
Commonwealth Scientific and
Industrial Research Organization,
Canberra, Australia*

References

1. D. E. Nelson and E. J. Amdur, in *Humidity and Moisture*, A. Wexler, Ed. (Reinhold, New York, 1965), vol. 1, p. 617.
2. R. O. Slatyer and J. F. Bierhuizen, *Plant Physiol.* **39**, P5 (1964).
3. D. T. Acheson, in *Humidity and Moisture*, A. Wexler, Ed. (Reinhold, New York, 1965), vol. 3, p. 521.
4. C. P. Hedlin and F. N. Trofimenkoff, in *Humidity and Moisture*, A. Wexler, Ed. (Reinhold, New York, 1965), vol. 1, p. 627.

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