ABSTRACT

Objectives. Surveys on winter depression in Iceland indicate a significantly lower prevalence rate of winter SAD than expected according to Iceland’s latitude. Research into daylight availability in Iceland failed to reveal factors contributing to higher average daylight availability than predicted by latitude. In view of the well-known healing effects of bright light treatment, we propose that properties of daylight other than daylight availability may ease the symptoms of winter depression.

Method. We analysed the spectral composition of daylight in Iceland as expressed by its chromaticity and assessed its seasonal and diurnal variations. The colorimetric properties of daylight during the year 1998 are dealt with in detail. Perception of daylight is modelled, applying the chromaticity model of MacLeod and Boynton along with environmental data on spectral irradiance recorded on location at 64°8.8’ N and 21°55.8’ W in Reykjavik, Iceland, and recently published data on cone fundamentals by Stockman and Sharpe.

Results. The main finding is that blue hue dominates the colour of the sky, with high correlated colour temperature, without significant seasonal variations. Diurnal variations are, however, observed. Furthermore, significant deviation from ‘standard’ sky is detected.

Conclusions. It is not known whether the observed chromaticity of daylight is a significant factor in explaining the unexpectedly low prevalence rate of seasonal affective disorder in Iceland. (Int J Circumpolar Health 2004;63(2):145-156)

Key words: Daylight, irradiance, chromaticity, seasonal affective disorder, Iceland
INTRODUCTION

The seasonal affective disorder (SAD), referred to as winter SAD, is a condition of regularly-occurring depression in fall and winter, with remission during spring and summer (1). Although winter depression has long been popularly recognized for instance in Iceland (2), the formal recognition and description of SAD as a specific syndrome dates only from the 1980’s, largely due to the efforts of Rosenthal and his colleagues. In their work, the responsiveness of SAD to phototherapy was a point of special emphasis (3,4), and SAD thus came to be viewed, early on, as a condition produced by ambient-light deficiency.

This understanding of SAD was reinforced by epidemiological research, which was much facilitated by the development of the Seasonal Pattern Assessment Questionnaire (SPAQ), by Rosenthal and co-workers (5,6), and of the SPAQ criteria for SAD and sub-syndromal SAD (S-SAD) subsequently developed by Kasper and associates (7,8). Most subsequent epidemiological research on SAD has made use of these tools.

In an influential study published in 1990, Rosen, Rosenthal and co-workers used the SPAQ to determine the prevalence of SAD and S-SAD (a milder form of the seasonal disorder (8)) at four locations along the Eastern Seaboard of the United States: Sarasota, Florida (latitude 27°N), Montgomery County, Maryland (latitude 39°N), New York City (latitude 40°N), and Nashua, New Hampshire (latitude 42.5°N) (9). Their study indicated that the prevalences of SAD and S-SAD correlated positively with latitude; and this result was consistent with earlier surveys, not based upon the SPAQ (10,11).

The idea that the prevalence of SAD increases with increasing latitude, due to decreasing of winter ambient light, has sometimes been referred to as "the latitude hypothesis" (12). The descriptive element of this hypothesis (direct dependence of prevalence with latitude) seemed, for over a decade, to be simply the natural reflection of its underlying aetiological element (ambient-light deprivation as the principal causal factor in SAD). Furthermore, the aetiological element seemed, indeed, amply justified by the ongoing work on SAD and bright light therapy. The received understanding of winter SAD as a light-deficiency disease was reinforced by the finding that, while winter SAD responds well to light treatment, "summer SAD", described by Wher et al. (13) and by Boyce and Parker (14), does not (8).
In 1993, Magnusson and Stefansson published the results of a SPAQ-based study on SAD conducted in Iceland (at 63.4°-66.5°N latitude) (15). This study revealed that the prevalence rates for SAD and S-SAD were markedly lower in Iceland than in three of the American locations studied by Rosen et al. (9), locations lying 21°-27.5° south of Iceland. Magnusson and Axelsson (16) found, in addition, that the combined prevalence of SAD plus S-SAD in Manitobans of wholly Icelandic descent (living at approximately 50.5°N latitude) was only marginally higher than that reported by Rosenthal and co-workers in Sarasota, Florida, lying 23.5° to the south of Iceland (9). These findings contradicted the descriptive element of the latitude hypothesis and, by implication, questioned the assumption that light deprivation could be viewed as the sole aetiological factor of importance in the expression of SAD. It was suggested that genetic factors might play an important causal role in SAD, and this idea received support in studies published by Stefansson et al. in 1994 (17) and in further studies by other researchers (18,19), which appeared shortly thereafter.

The fact still stands that surveys on winter depression in Iceland measure a significantly lower prevalence rate of SAD than expected according to the "latitude hypothesis" (12,15-17,20). Furthermore, research into daylight availability in Iceland failed to reveal factors, such as snow cover, contributing to illuminance, which might explain higher average daylight availability than predicted by latitude (20). However, in view of the well-known healing effects of light treatment (21), we propose that properties of daylight other than daylight availability may ease the symptoms of winter depression. In other words, we postulate that it is not only the quantity of daylight, but other properties that may ease the SAD symptoms. One of these qualities is the ‘prevailing’ spectral composition of daylight, which can be quantified by appropriate colour models. Hence, the main objective of this study is to assess the chromaticity of daylight in Iceland as well as its seasonal and diurnal variations. In the following, the colorimetric properties of daylight are exemplified using radiometric data from the year 1998. These data are subsequently analysed applying the MacLeod-Boynton chromaticity model (22) and recently published cone fundamentals by Stockman and Sharpe (23,24). By doing this, an overview of perceived colour of daylight is obtained.
METHODS

Study design
A one-year study of spectral irradiance on a horizontal surface in Reykjavik.

Environmental Data
The data on daylight used in the present study was recorded under the auspices of the Engineering Research Institute of the University of Iceland, during the period 1991 to 2002 at 64°8.8' N and 21°55.8' W in Reykjavik, Iceland. The data contains both information on illuminance and spectral irradiance on a horizontal surface. The illuminance is sampled once every minute. The spectral irradiance is, on the other hand, recorded at least once every hour, covering wavelengths from 280 nm to 786 nm, with 1-nm resolution. The instrument applied was a spectral radiometer of the type OL 752 from Optronics Laboratory Inc.

The processing of the data was carried out using software developed by the Engineering Research Institute. The ultraviolet range is divided into UV-C (100-280 nm), UV-B (280-315 nm) and UV-A (315-400 nm), according to the Commission Internationale de l’Éclairage (25). It is seen that the absorption processes in the atmosphere shape the spectrum. The 760-nm absorption band for oxygen is a dominating feature in the long wavelength part of the spectrum. The short wavelength part of the spectrum is shaped by the ozone content of the atmosphere and the activity of the sun.

The daily variation of the spectral irradiance follows the elevation of the sun as indicated in Figure 1, showing data for clear-sky conditions, as well as variable overcast conditions. In the early morning and late evening, the intensity is low, with a higher relative contribution from long-wave radiation than is the case when the sun is highest in the sky. Figure 1a reflects the symmetry in the spectral irradiance around high noon, as expected on theoretical grounds for clear-sky conditions. On the other hand, this is not necessarily the case for days with cloudy conditions, as indicated in Figure 1b. In general, it is found that the irradiance typical to Icelandic weather conditions is characterised by great variability dominated by short-term fluctuations.
Figure 1. An example of spectral irradiance as a function of wavelength measured at different hours. (a) A sunny day, the 7th of June 1998. (b) A cloudy and hazy day, the 23rd of June 1998.
Procedure

The perception of daylight and its colours is examined below applying the chromaticity model of MacLeod and Boynton (22), along with the environmental data on spectral irradiance described above and recently published data on cone fundamentals by Stockman and Sharpe (23,24).

The cone fundamentals describe the spectral sensitivity of the cones in the retina of the eye, referred to in the following as L-, M- and S-cones, i.e., long, medium and short wavelength cones. The cone fundamentals can be visualised as colour-matching functions (26) for three imaginary colours. Each of these three imaginary colours stimulates only one cone type, and their effects are considered to be independent. Figure 3 displays the applied cone fundamentals (23,24), showing cone sensitivity as a function of wavelength. The response value of the cone fundamentals for a given wavelength is always greater than zero, contrary to the colour-matching functions.

Perception of the luminance of daylight is especially related to the L- and M-cones, while the contribution of S-cones is disputed (27). However, it has been shown that their contribution may be significant in some cases, especially when the L- and M- cones are under strong effects from a wide-range spectral power. As the contribution from the S-cones is generally limited and in a narrow wavelength range, it is generally accepted that their part in illuminance perception can be neglected. Hence, following Stockman and Sharpe (23,24), it is assumed that the photopic illuminance can be obtained using a photopic efficiency curve that is the sum of the L- and M-cone fundamentals (see Figure 2).

Several colorimetric models are available based on three-dimensional colour space. The best known model is the so-called CIE model (Commission Internationale de l’Éclairage-model). This model and similar ones have been criticised from a perception-psychological point of view (28), as they are not founded on well-defined perception processes and the cone excitation space. According to Rodieck (27), however, it is possible to derive the CIE model from the cone excitation space by applying non-orthogonal transformation, resulting in a non-orthogonal coordinate system.

Recently, the chromaticity model put forward by MacLeod and Boynton (22) has gained increased recognition and wide application. This model is based on the principles of sensory psychology and the physiology of the human eye. The basic assumption is that the perceived illuminance can be modelled by L- and M- cones independent of the S-cones. This leads to the definition of the equiluminous chromaticity plane suggested by MacLeod and Boynton (22).
The MacLeod-Boynton chromaticity diagram is shown in Figure 3, where the l-chromaticity coordinate is represented by the horizontal axis (positive direction towards right), and the s-chromaticity coordinate is along the vertical axis. This representation gives chromaticity coordinates with equiluminous colours (22,28). It is common to scale the s-coordinate so its theoretical peak value equals one (22-24). The spectral locus, Planckian locus and equal energy white point are all derived using Stockman and Sharpe cone fundamentals (see Figure 2). The chromaticity of daylight is exemplified in Figure 4. Each point represents the colour of the sky at 1-hr time intervals.

RESULTS AND DISCUSSION

A MacLeod-Boynton chromaticity diagram derived from the irradiance recorded during January, April, July and October is shown in Figure 4. The chromaticity coordinates are, in all cases, close to the Planckian
Figure 3. MacLeod-Boynton-chromaticity diagram. The grey scale curve signifies the spectral locus, which ranges from approximately 400 to 700 nm. Wavelengths in nm are marked on the curve. The straight line representing aspectral colours connects the two ends of the grey scale curve, which are at 400 and 700 nm. The black curve through the white dot is the Planckian locus, which is calculated by aid of the theoretical power spectral density for a black body. The white dot indicates an equal-energy white corresponding constant power spectral density.

locus, but tend to be on its left side, i.e., the chromaticity coordinate for the sky is, on average, lower than the corresponding chromaticity coordinate of the Planckian locus, assuming the same S-coordinate in both cases. It is also observed that the chromaticity coordinates tend to diverge from the Planckian locus as the S-coordinate increases, which may perhaps be interpreted as a deviation from the so-called CIE standard sky, which is close and almost parallel to the Planckian locus (26). It is also characteristic that the bulk of the observed chromaticity is located above the equal energy white point and with a correlated colour temperature higher than about 5 000 K. This indicates that the main colour characteristics of the sky are blue. There was no statistically significant difference between months in this respect. This property seems to contradict published results (26,29). It is, however, possible that this can be regarded as a scientific explanation of "the
blue light of the North” commonly referred to in connection with art and painting. In view of this, it is worth investigating the diurnal variation in the colour of the sky. The main finding seems to be that the chromaticity of the sky in early morning and late evening is characterised by a blue colour corresponding to a very high correlated colour temperature, usually more than 20 000 K. During the middle of the
day, when the elevation of the sun is highest, the chromaticity approaches the equal energy white point. This result seems to contradict the result presented by Malacara (30). He points out that the colour of the sky is more towards the red in the morning and the evening, but more in the range of blue during the middle of the day. In this context, it is worth pointing out that the recorded irradiance represents a hemispherical average value on a horizontal surface. Furthermore, it is worth noting that, when the sun goes down, the relative contribution of spectral irradiance in long wavelengths increases, i.e., radiant energy in the red and infrared range increases. This measured increase in long-wave radiant energy does not seem to be perceived as yellow or red colours by the human eye, as the sensitivity of the cones is small in these wavelength ranges; in other words, the cone fundamentals are almost zero, which implies that the contribution to the chromaticity coordinates is insignificant.

To substantiate the above-mentioned finding, a photographic field survey was carried out in Reykjavik during the period September to December 2002. It was observed that the sunset on sunny days with clear-sky conditions was characterised by a thin red and yellow band at the horizon in the West, while the colour of the sky was mainly in blue hues, ranging from light blue to dark blue, almost black, in the East. Similar results were obtained for partly overcast days. In view of these investigations, the findings derived from the irradiance data seem credible. However, this requires closer investigation, as it has not been ruled out that the location of the instrument may play a role when the sun is low in the sky. Nonetheless, the observed blue light in Iceland seems to be a fact.

The beneficial effect of light is widely supposed to relate to its interference with melatonin secretion. Karadottir and Axelsson (31) measured melatonin in saliva by the RIA method developed by Vakkuri (32) and found its concentrations to be, on average, 2.4 times higher in SAD patients than in the control group. Furthermore, Skene (33) found that light-induced melatonin suppression was sensitive to short wavelengths of light (420-480 nm), i.e. blue light. This is a clear indication of the favourable mitigating effects that short wavelength light has on SAD, which in turn suggests that the Icelandic blue light may be a factor contributing to the low prevalence of SAD in Iceland.
CONCLUSIONS

It is found that the chromaticity data falls around, or near to, the Planckian locus (the theoretical black body radiation curve). Furthermore, it is observed that the correlated colour temperature is, in general, higher than expected throughout the year, in most cases around and above ~5.000 K (near the ‘white point’). This implies that the colour of the daylight (the sky’s colour) ranges, in the majority of cases, from white to blue, and seems to be fairly stable in every month of the year. The warm ‘reddish’ chromaticity observed at ‘southern’ latitudes is rare in the Icelandic data studied. Finally, it is observed that the chromaticity of daylight deviates from what seems to be characteristic of southern latitudes. However, it remains to be seen whether, or not, this is a quantitatively significant factor in explaining the unexpectedly low prevalence of SAD in Iceland.

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REFERENCES

1. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders : DSM-IV (4th ed). Washington, DC: American Psychiatric Association 1994.
2. Magnusson A, Axelsson J. SAD in Iceland. Light Treatment and Biological Rhythms 1993;5(4):57-58.
3. Rosenthal NE, Sack DA, Gillin, JC et al. Seasonal affective disorder: A description of syndrome and preliminary findings with light therapy. Arch Gen Psychiatry 1984;41(1):72-80.
4. Rosenthal NE, Sack DA, Carpenter CJ, Parry BL, Mendelson WB, Wehr TA. Antidepressant effects of light in seasonal affective disorder. Am J Psychiatry 1985;142,163-170.
5. Rosenthal NE, Bradt GH, Wehr TA. Seasonal Pattern Assessment Questionnaire. Bethesda (MD): National Institute of Mental Health; 1987.
6. Rosenthal NE, Gernhart MJ, Sack DA, Skwerer RG, Wehr TA: Seasonal affective disorder and its relevance for the understanding and treatment of bulimia. In Hudson JJ, Pope HG Jr. (eds.), The Psychobiology of Bulimia, American Psychiatric Press, Washington, D.C., 1987, pp. 205-228.
7. Kasper S, Rogers SLB, Yancey A, Schulz PM, Skwerer RG, Rosenthal NE. Phototherapy in Individuals With or Without Subsyndromal Seasonal Affective Disorder. Arch Gen Psychiatry 1989;46:837-844.
8. Kasper S, Wehr TA, Bartko JJ, Gaist PA, Rosenthal NE. Epidemiological findings of seasonal changes in mood and behavior: A Telephone Survey of Montgomery County, Maryland. Arch Gen Psychiatry 1989;46:823-833.
9. Rosen LN, Targum SD, Terman et al. Prevalence of seasonal affective disorder at four latitudes. Psychiatry Res 1990;31:131-144.
10. Lingaerde O, Brathlid T, Hanse T, Gotestam K. Seasonal affective disorder and midwinter insomnia in the far north: studies of two related chronobiological disorders in Norway. Clin. Neuropharmacol 1986;9 (Suppl. 4):187-189.
11. Potkin SG, Zetin M, Stamenkovich V, Kripke D, Bunney WJ. Seasonal affective disorder: prevalence varies with latitude and climate. Clin Neuropharmacol 1986;4,181-193.

12. Axelsson J, Stefansson JG, Magnusson A, Sigvaldason H, Karlsson MM. Can J Psychiatry 2002;47(2):153-158.

13. Wehr TA, Sack DA, Rosenthal NE. Seasonal affective disorder with summer depression and winter hypomania. Am J Psychiatry 1987;144:1602-1603.

14. Boyce P, Parker G. Seasonal affective disorder in the southern hemisphere. Am J Psychiatry 1988;145(1):96-99.

15. Magnusson A, Stefansson JG. Prevalence of seasonal affective disorder in Iceland. Arch Gen Psychiatry 1993;50:941-946.

16. Magnusson A, Axelsson J. The prevalence of seasonal affective disorder is low among descendants of Icelandic emigrants in Canada. Arch Gen Psychiatry 1993;50(12):947-951.

17. Stefansson JG, Magnusson A, Karlsson MM, Axelsson J. Low prevalence of seasonal affective disorders in Icelanders and Canadians of Icelandic descent. In G. Petursdottir, S.B. Sigurdsson, M.M. Karlsson, & J. Axelsson (editors), Proceedings of the 9th International Congress on Circumpolar Health, Reykjavik. Arctic Med Res 1994;53(suppl 2):491-492.

18. Ozaki N, Ono Y, Ito A, Rosenthal NE. Prevalence of seasonal difficulties in mood and behaviour among Japanese civil servants. Am J Psychiatry 1995;152:1225-7.

19. Madden PA, Heath AC, Rosenthal NE, Martin NG. Seasonal changes in mood and behaviour: The role of genetic factors. Arch Gen Psychiatry 1996;53(1):47-55.

20. Axelsson J, Ragnarsdottir S, Pind J, Sigbjornsson R. Daylight availability: A poor predictor of depression in Iceland. Submitted for publication to Int J Circumpolar Health 2004.

21. Partonen T, Magnusson A. (Eds.). Seasonal Affective Disorder: Practice and Research. Oxford, UK: Oxford University Press 2001.

22. MacLeod DIA, Boynton RM. Chromaticity diagram showing cone excitation by stimuli of equal luminance. J Opt Soc Am 1979;69:1183-1186.

23. Stockman A, Sharpe LT. The spectral sensitivity of the middle- and long-wavelength-sensitive cone derived from measurements in observers of known genotype. Vision Res 2000;40(13):1711-1738.

24. Stockman A, Sharpe LT. Tritanopic color matches and the middle- and long-wavelength-sensitive cone spectral sensitivities. Vision Res 2000;40(13):1739-1750.

25. Rea MS (editor-in-chief). Lighting Handbook: Reference and Application. New York: Illuminating Engineering Society of North America 1993.

26. Wyszecki G, Stiles WS. Color Science: Concepts and Methods, Quantitative Data and Formulae. New York: John Wiley & Sons, Inc 1982.

27. Rodieck RW. The First Steps in Seeing. Massachusetts, USA: Sinauer Associates, Inc 1998.

28. Kaiser PK, Boynton RM. Human Color Vision (2nd edition). Washington, DC: Optical Society of America 1996.

29. Henderson, S.T. Daylight and its Spectrum. Bristol: Adam Hilger Ltd 1977.

30. Malacara D. Color Vision and Colorimetry: Theory and Applications. Washington, USA: SPIE – The International Society for Optical Engineering 2002.

31. Karadottir R, Axelsson J. Melatonin secretion in SAD patients and healthy subjects matched with respect to age and sex. Int J Circumpolar Health 2001;60:548-551.

32. Vakkuri O. Diurnal rhythm of melatonin in human saliva. Acta physiol Scand 1985;124,409-412.

33. Skene DJ. Optimization of Light and Melatonin to Phase-Shift Human Circadian Rhythms. J Neuroendocrinol 2003, 15, 438-41.

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