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A thermographic promenade through the Berlin Botanic Garden

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Dedicated to Professor Wolfgang Hemminger on the occasion of his 65th anniversary.

Abstract

False colour infrared (IR) thermography was performed on a sunny summer day in the Berlin Botanic Garden. The main interest focused on blossoms of different size, colours and shapes: disk-, bowl- and funnel-like anatomy demonstrating various modes of light absorption and heating-up during the day. Some of the flowers were phototropic or even solar tracking. Blossom temperatures ranged from 18.0 to 33.3 °C (mean 26.3 ± 2.5 °C, S.D., $n = 37$) at 21 °C air temperature. Several thermograms showed honey- and bumblebees also. In some cases the results are compared with those of a contact-free IR thermometry. One winter- and one late-spring-flowering plant are included in the overview.

Keywords: Infrared; Insects; Plants; Thermography; Thermometry

1. Introduction

False colour infrared (IR) thermography – also called thermal or infrared imaging, infrared radiometry or IR condition monitoring – is best known for technical applications to detect heat sources in electronic devices, friction in rotating parts of engines, lack of insulation of buildings or voids and inhomogeneities close to the surface of single and multilayered building structures [1–5]. Medical questions concern among others IR condition monitoring, metabolic and vascular disorders, breast cancer, arthritis or diabetes [6] or computer regulation thermography (CRT). Plants are out off focus for thermography and rather seldom investigated [7]. Papers up to now concerned thermogenic plants [8–14], virus infections [15–17] and withering by cold [18–21]. A short survey over this field is given by one of the authors in [22]. Most botanic applications were performed under laboratory conditions while we want to show in this paper the facilities of outdoor thermography.

Visitors to a botanic garden enjoy the beauty of the various flowers, their smell and the different colours of the leaves. Natural scientists do the same, but moreover, further details stimulate their curiosity additionally. For most of their life, plants have significantly lower metabolic rates than animals so that their organs are mainly at ambient temperatures. Why then infrared thermography? A homogeneous one-colour picture has to be the result; except perhaps for the floral interplay with the solar irradiation of absorption and reflection. Our interest started with investigations on two plant groups of energy specialist, the phototropists and the thermogenics, and enlarged to other flowers, which – due to their form – should collect radiation intensively and heat up in this way.

Phototropism means an orientation of plants or part of a plant to a light source, often the sun (heliotropism). In this way the absorbing surface can be increased for a larger photosynthetic yield or decreased to avoid overheating and a too high consumption of water for cooling. Most sophisticated are the solar trackers that follow the path of the sun for several hours or – in arctic regions – during the whole day. The Mountain Aven *Dryas octopetala* (see below) belongs to them. Thermogenic plants are a heterogeneous group of ancient seed plants that switch over from the usual to an alternative metabolic pathway during their inflorescence and dissipate most energy as heat [23]. Special parts of their flowers increase the temperature to distribute odour and to attract pollinators. Most beautiful among them are the sacred lotus *Nelumbo nucifera* and the giant tropical water lilies *Victoria amazonica* or *V. cruziana*. Although they are highlights of a promenade through a botanic garden, they shall be omitted here as they were intensively discussed earlier by the authors

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[24,25]. The same holds good for the voodoo lily *Sauromatum guttatum* and the exotic elephant yam *Amorphophallus paeoniifolius* [26].

2. Material and methods

2.1. IR false colour camera

The geometrical distribution of the surface temperature of most blossoms was determined as spectral radiation density in the near infrared between 3.5 and 5 μm. For this end, an infrared camera (Inframetrics SC1000, FLIR Systems, Germany) was applied with a focal-plane array of 256 × 256 detector elements (Pt–Si-Schottky diodes) equipped with a Stirling microcooling device. To remain flexible in the Botanic Garden we chose the battery mode with the camera attached to a heavy tripod. The "Auto Span" key provided the maximum and minimum viewable temperatures within the frame, while the "Span" mode allowed adjusting the optimal width of the temperature range of interest. Images were stored as tif-files on a flash card that was read out to the computer later on. In the presented thermograms, an emissivity of 0.95 was used representing a typical value for plants.

Temperature evaluation was performed in the "Iron" mode of the camera. As a flying-spot cursor was not available, the images were imported into Adobe PhotoShop. The eye-dropper tool served together with the Navigator Info to compare colours in the picture and on the right-hand scale. Temperatures were read to 0.1 °C. Due to the low number of pixels in the thermographic image (66 kpixel) compared to several Mpixel of modern DC cameras the geometrical resolution is rather coarse. To compensate this drawback, optical photographs of the same blossoms are shown aside in Figs. 2 and 3.

2.2. Time and localisation of the photo promenade

As the thermographic camera was available for a rather short time only, a suitable date was chosen in summer when many flowers were blooming to obtain a broad spectrum of structures, forms and colours. This approach had the disadvantage that short-period blossoms, especially the late-winter and early-spring bloomers or rare aroids were excluded. To compensate for this deficit, such plants were monitored by IR thermometry (handhold thermometer, THI 300, Tasco, Japan, spectral band 6–12 μm corresponding to −30 to +200 °C) and scanning their surface by hand. One example is included in this report. Often, thermogenic plants flower for a day or even only hours so that it is difficult to find the correct time of their inflorescence.

The thermographic images were taken on the 1st of September 2005 between 10 am and 1 pm in the Botanic Garden of the Free University of Berlin. Interesting blossoms were seen in the numerous ornamental parts of the garden as well as in the geographical, officinal and systematical divisions. It was a clear sunny late-summer day with mean air temperatures of 21 °C in the shade, but significantly higher ones at sunny spots. If possible, photos were taken at the latter places. In some cases blossoms were artificially shaded and investigated again after a first sunny approach. Some flowers showed still signs of the morning irrigation. This could not be avoided since we had to integrate into the time schedule of the garden.

3. Results

3.1. General observations

IR thermograms of 47 objects were taken during our promenade, sometimes a flower in sun as well as in shade; and not only blossoms, but larger fruits like pumpkins (Summer Squash *Cucurbita pepo*), hips (*Rosa rugosa*), ripening artichokes (*Cynara scolymus*) or the decorative envelop of the Chinese Lantern (*Physalis alkekengi*). The most interesting 24 objects are collected in Table 1, with seven pairs of sun/shade thermograms. Size and form of the blossoms varied considerably, from a few centimetres for the Californian Poppy (*E. californica*) to more than 30 cm for a Sunflower (*H. annuus*) and from disk-like flat over bowl-shapes to funnel-like characters of the Morning Glory (*I. tricolour*) or the Garden Nasturtium (*T. majus*).

Table 1 gives a survey over the different plants and varying photo conditions during the promenade. Besides the official Latin botanical designation a popular English name is cited, although the authors know that such names change from region to region. The widespread Dandelion (*Taraxacum officinale*) has more than 500 popular names in German-speaking countries, and this will be the same in other countries. Minimum and maximum temperatures as well as their differences can be read from Table 1 together with the influence of artificial shading of some flowers.

Thermograms of blossoms were taken scaled to the maximum and minimum temperatures within the frame. 0.1 K temperature differences and distances of 2 mm could be resolved. Temperatures varied from 17.2 to 33.8 °C with means of 21.6 (±2.1 S.D., n = 37) and 29.8 (±2.3) °C for minimum and maximum values, respectively, in all essential images recorded during the promenade. Later on, the thermograms were scaled to the extreme values of the most prominent blossom in each picture to obtain the highest possible temperature resolution. These values stretched from 18.0 to 33.3 °C with means of 23.1 (±2.4) for the minimum and 29.4 (±2.6) °C for the maximum. Temperature differences found in the blossoms ranged from 2.1 to 10.7 K with a mean of 6.0 (±2.2 S.D., n = 36) K.

In seven cases flowers were artificially shaded to estimate the total cooling rates in different parts of the blossoms without differentiation between loss by conduction, convection, or evaporation. To this end, a second picture was taken after 1 min. During this period the maximum temperatures dropped by 2.5 (±1.7) K as the mean for a gradient of 9.1 K against the surrounding. The decrease of the minimum value was significantly smaller with 0.7 (±0.7) K due to the lower gradient of only 1.7 K. But the specific rates were approximately the same with 0.3 and 0.4 K K^{-1} min^{-1}, respectively. These high cooling rates are due to the unfavourable surface-to-volume ratio of the flat leaves and petals. In several thermograms it became obvious that strongly differing temperatures existed near to one another. A Garden Zinnia (*Z. elegans*) showed 5.5 K over 0.6 cm (9.2 K cm^{-1})

Table 1
List of plants investigated with IR false colour thermography

Botanical name	English name	B_{max} (°C)	B_{min} (°C)	ΔT (K)
Brugmansia suavolens	Angels' Trumpet	26.0	21.3	4.7
Brugmansia suavolens	Angels' Trumpet	27.1	21.4	5.7
Calendula officinalis	English Marigold	33.3	22.7	10.6
Chrysanthemum coronarum	Crown Daisy	27.6	23.3	4.3
Chrysanthemum coronarum	Crown Daisy	*26.9*	*22.8*	*4.1*
Chrysanthemum coronarum	Crown Daisy	29.3	23.8	5.5
Cichorium intybus	Common Chickory	30.3	24.7	5.6
Colchicum autumnale	Meadow Saffran,	30.5	23.4	7.1
Colchicum autumnale	Meadow saffran,	29.7	24.3	5.4
Cosmea sp.	Cosmea	29.0	19.7	9.3
Dahlia sp.	"Gräfin Cosel"	30.6	22.4	8.2
Dahlia sp.	"Schloss Reinbeck"	28.8	24.8	4.0
Dahlia sp.	"Schloss Reinbeck"	*26.0*	*23.0*	*3.0*
Dryas octopetala[a]	Mountain Avens	30.9	27.2	3.7
Eschscholzia californica	California Poppy	27.9	22.9	5.0
Helianthus annuus	Sunflower	24.3	18.0	6.3
Helianthus annuus	Sunflower	32.9	27.3	5.6
Helianthus annuus	Sunflower	28.2	24.7	3.5
Helianthus salicifolius	Willow Leaf Sunflower	29.9	19.2	10.7
Heliopsis helianthoides	Ox-eye Sunflower	31.9	23.5	8.4
Ipomoea tricolour	Morning Glory	30.8	21.1	9.7
Ipomoea tricolour	Morning Glory	*26.7*	*23.8*	*2.9*
Lactuca serriola	Prickly Lettuce	30.5	21.1	9.4
Lactuca serriola	Prickly Lettuce	*25.9*	*20.4*	*5.5*
Lantana camara	Yellow sage	28.7	26.6	2.1
Nymphaea sp.	Water Lily	29.7	24.3	5.4
Oenothera missouriensis	Missouri Evening Primrose	29.3	23.0	6.3
Physalis alkekengi	Chinese Lantern	37.5	29.1	8.4
Rudbeckia fulgida	Black-eyed Susan	33.0	25.1	7.9
Rudbeckia fulgida	Black-eyed Susan	*30.5*	*25.3*	*5.2*
Silphium laciniatum	Compass Plant	26.4	20.2	6.2
Silphium laciniatum	Compass Plant	27.0	19.6	7.4
Tagetes sp.	Marygold	32.9	26.3	6.6
Tropaeolum majus	Garden Nasturtium	30.0	22.1	7.9
Tropaeolum majus	Garden Nasturtium	*27.0*	*22.0*	*5.0*
Zinnia elegans	Garden Zinnia	30.0	22.4	7.6
Zinnia elegans	Garden Zinnia	*30.0*	*22.0*	*8.0*
Mean		29.4	23.1	6.0
Standard deviation		±2.6	±2.4	±2.2

B_{max}, B_{min}: maximum and minimum temperatures in the blossoms; ΔT: temperature difference. Italics: thermograms taken in the shade.
[a] Thermogram taken in early summer.

between the centre and the base of the petals or 12.8 K cm^{-1} within the centre. In a few cases there were still water drops from irrigation on the blossoms appearing as cool black spots in the thermograms. Here, the temperature gradients varied between 8 and 10 K cm^{-1}.

Sometimes, honeybees and bumblebees were photographed together with the blossoms (Fig. 3). They were significantly warmer than the flowers as thorax temperatures during flight amount to about 36 °C for honeybees, with a much cooler abdomen [27]. The thoracic flight temperature of bumblebees is slightly higher [27,28]. Thus, temperatures of both insects are out of the scaled range for the blossoms and show the animals as white spots. From the initial overall thermogram of a Crown Daisy (*Chrysanthemum coronarium*) with a honeybee we determined 36.3 and 30.6 °C for thorax and abdomen, respectively. A honeybee that rested a while in a Dahlia blossom cooled down to 32.2 and 31.5 °C in thorax and abdomen, respectively.

3.2. Individual thermograms

To show a broader spectrum of thermal investigations in the Botanic Garden, one example of a late-winter bloomer shall be presented here. The Far East Amur Adonis (*Adonis amurensis*) appears in March when there is still a closed layer of snow and low night temperatures (Fig. 1). It buds through the snow and opens its sulphur-yellow blossoms and its dark-green leaves about 10 cm above the snow. The bowl-shaped flowers are phototropic in the sense that they adjust more or less exactly to the zenith, a position that grants maximum radiation absorption when the flower does not track the sun. Random orientation of blossoms would reduce the energy gain of the plant. At air temperatures around the freezing point the yellow bowls become up to 10 K warmer than the environment, as does the dark brown litter beneath the flowers. In this way open areas are created around the base of the stem, so that the roots of the plant may also profit

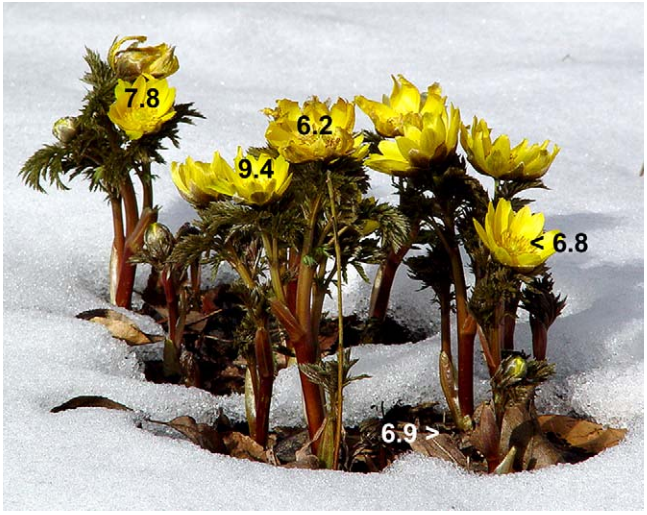


Fig. 1. The Amur Adonis *Adonis amurensis* flowering in the first sunny days of March in the Botanic Garden of Berlin (around noon, about 0 °C). Surface temperature differences against air in degrees Kelvin of sulphur-yellow blossoms and last-year leaves were determined by an IR thermometer. The bowl-shaped crown leaves collect the radiation and protect against wind.

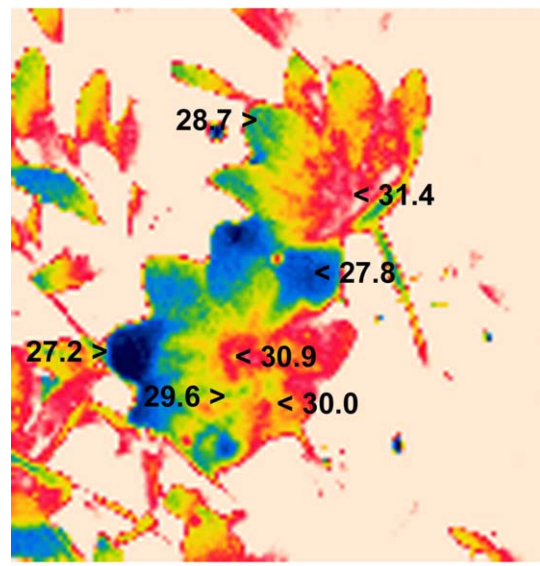
from the additional energy gain. It could not be proved if pollinating insects also take advantage of the elevated temperature and the protection against wind inside the bowl. Such assertions are well known from alpine and arctic plants [29].

The Mountain Aven *Dryas octopetala* was the only plant thermographically investigated in the early summer in connection with heliotropism and solar tracking [26]. This creeping shrub from alpine regions shows beautiful white blossoms with numerous yellow pistles (Fig. 2a). Dryas blossoms do track the sun and concentrate the radiation to their centre by means of the parabolic bowl-shaped corollas. Temperature increases by several degrees, increasing the flowering speed and the ripening of pollen. Moreover, pollinators receive heat rewards from the bowls in the rather cold environment, which makes flight an energy consuming business [30,31].

Fig. 2b shows two Dryas blossoms with focus temperatures of 31.4 and 30.9 °C, 2.7–3.7 K warmer than the surrounding white petals and about 15 K above air temperature. Soil and many of the green leaves around the blossoms are even warmer, out of the chosen temperature range. Thus, it should be easier for an insect to absorb heat for flight there and not in the blossom. Supposedly, the combination of white and yellow colours in the blossom, the increased temperature and the protection against wind is a convincing argument for a pollinator. Scanning numerous blossoms showed maximum temperature differences of up to 5.0 K between the centre and the corolla and a mean value of 3.6 K. IR thermometry as with the Amur Adonis gave similar values as in Fig. 2b.

To make recognition of the thermogram (Fig. 3b) easier, Fig. 3a shows an optical picture of a Crown Daisy (*Chrysanthemum coronarum*) that was frequently visited by honeybees. A honeybee is also visible in the lower image, down in the low left corner. The high thorax temperature of 36.3 °C indicates that the bee just landed aside the blossom. The corolla of this blossom is too flat or even bent a bit backwards to concentrate energy to the centre, so that the petals in full sun are several degrees warmer than the latter. Leaves are in general cooler than the blossom, in some parts already outside the chosen temperature range.

(a)



(b)

Fig. 2. Mountain Aven (*Dryas octopetala*) photographed in the early summer. The bowl-shape of the blossom becomes visible in both the optical (a) and the thermographic picture (b). The soil and most of the flat-lying leaves are warmer than the blossom and thus out of the chosen temperature range.

Figs. 4 and 5 are so typical for Dahlia (*Dahlia* sp.) and Blacked-eyed Susan (*Rudbeckia fulgida*) that the thermograms are presented without a corresponding optical equivalent. The first thermogram is scaled to the maximum and minimum temperatures in the whole frame ("Auto Span"; see Section 2.1), the second scaled to the extremes of the blossom ("Span"; see Section 2.1) so that colder parts of the picture are shown in black. Dahlia temperatures range from 22.0 °C in the lowest petals at the ground of the blossoms to 30.6 °C in yellow-white spots in the centre (Fig. 4). It seems as if this flower is illuminated from the inside. Presumably, air pockets are included between the different petals, which prevent loss of the absorbed heat. The Black-eyed Susan (*Rudbecki fulgida*) in the centre of Fig. 5

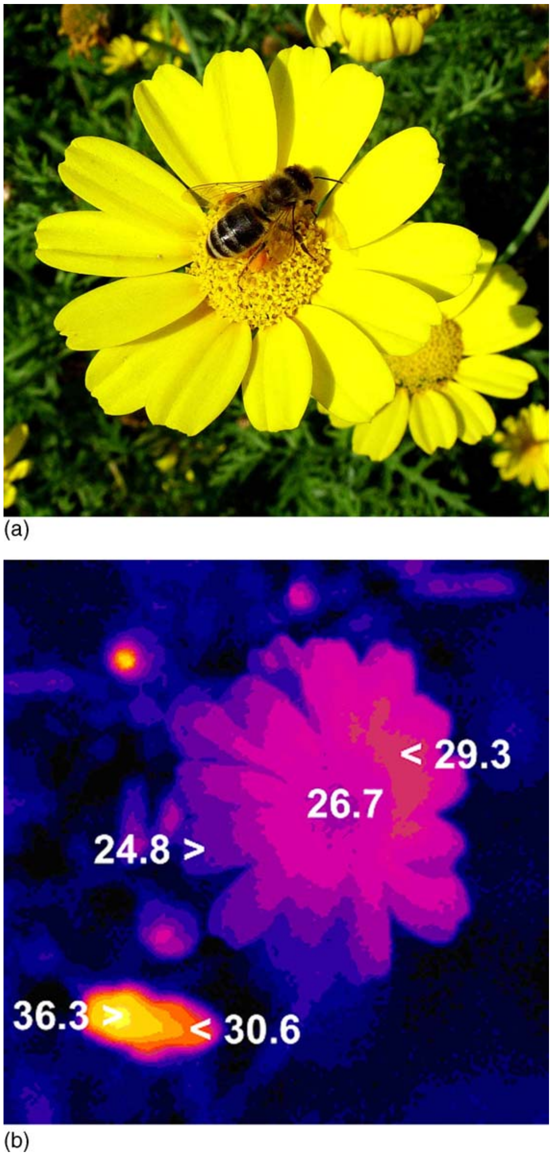


Fig. 3. Crown Daisy *Chrysanthemum coronarum* with a pollen-collecting honeybee (left). Please notice the orange pollen trousers on the back legs of the insect. The small brownish ring around the centre of the blossom at the base of the petals (also seen in the lower blossom behind) is also detectable with slightly elevated temperatures in the corresponding thermogram. Thermogram of a Crown Daisy with a visiting honeybee (right). Typical mean temperatures for the different parts are indicated. The blossom was in full sun, the bee just arrived at a leaf nearby. Its head and thorax point to the left.

exhibits minimum values (27.9 °C) at the tips of the petals, a maximum of 32.9 °C at the upper side of the centre and 29.8 °C in the "pupil of the eye". The additional ring structure of the blossom seen in UV photographs of this plant cannot be detected here in the IR range.

We were interested not only in blossoms during this promenade, but also in leaves in two cases — those of the famous compass plants *Lactuca serriola* (Fig. 6) and *Silphium laciniatum*. The Prickly Lettuce *L. serriola* is well known as compass plant through all Europe while *S. laciniatum* with the popular name Compass Plant is typical for the North American south. These plants turn their leaves in a vertical position due

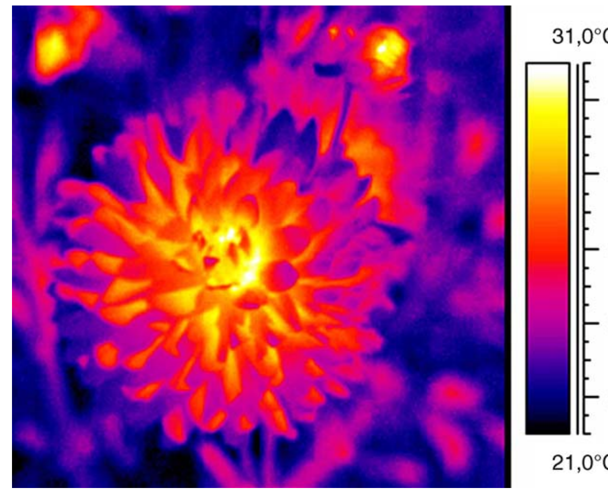


Fig. 4. Thermogram of a red-orange Dahlia named Gräfin Cosel (class: water lilies) in full sun. For further details see text.

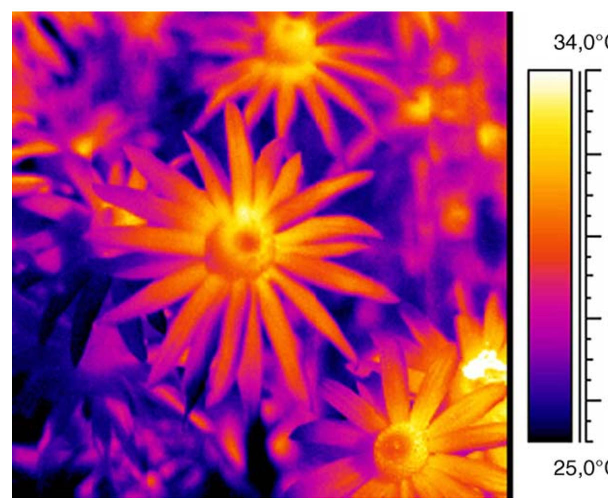


Fig. 5. Thermogram of several intensely yellow blossoms of the Black-eyed Susan (*Rudbeckia fulgida*) in full sun. Pay attention to the much colder background and the high central temperatures of these honeybee-attracting blossoms.

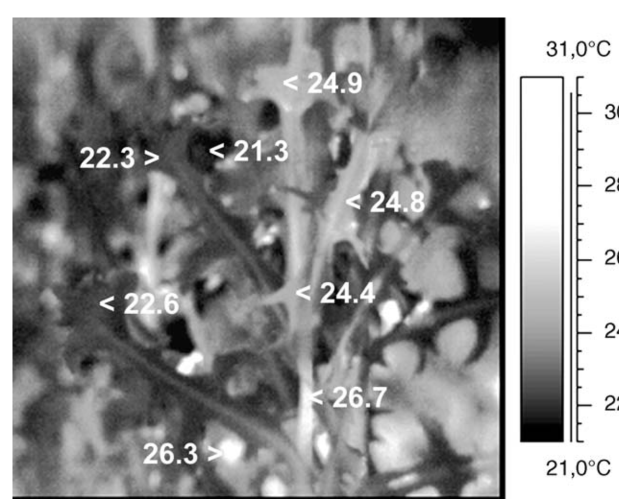


Fig. 6. Leaves of the Prickly Lettuce *Lactuca serriola* – the European compass plant – oriented N–S with temperatures significantly lower than those of the background and parts of the stem exposed to the sun.

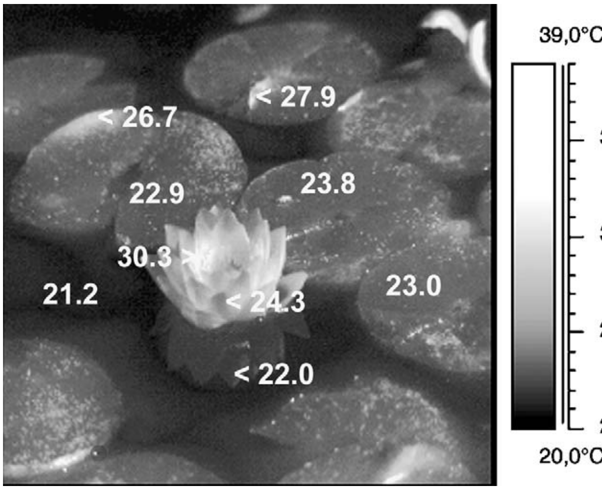


Fig. 7. Water lily (*Nymphaea* spec) in an outdoor basin of the Botanic Garden. Solar illumination from the right, clearly seen in the left inside of the blossom and the upright curled left edges of the leaves. Notice that the mirror-image of the blossom is cooler than the object itself (see text).

to energetic reasons. With a further turn they adjust all their leaves in a parallel direction pointing N–S, so that the majority of the leaf surfaces look E–W. Older leaves in the lower part are oriented, while the younger upper ones are more randomly turned. Nevertheless, these plants may serve as botanical compasses in the wilderness. With the E–W orientation the plant avoids the strong solar radiation at noon and a high water loss due to evaporation, which is of eminent importance in dry or arid regions of the Earth. On the other hand, they collect enough photosynthetically active radiation in the morning and the afternoon [32]. Thus, compass plants are comparable to the wedge-shaped "compass mounds" of the Australian *Amitermes meridionalis* termites strictly oriented N–S for the same reason [27]. Thermograms of *Lactuca* leaves show noon temperature differences of −3 to −6 K of oriented leaves compared with those facing the sun. Potted *Lactuca* plants that could be turned by 90° demonstrated differences in surface temperatures of 5–7 K between N–S and E–W orientation (determined by IR thermometry).

To show at least one water plant in this bouquet of garden beauties a water lily (*Nymphaea* sp.) is included in the promenade (Fig. 7). Its temperature spans from 22.5 to 30.9 °C with the maximum on the left side where the full sunlight hits it. This also becomes evident in the various upward bent rims of the flat leaves, which are up to 7 K warmer than the main body of the leaf. The tips of the blossom petals are cooler than the centre by a few degrees, presumably again due to the exposure to wind and an increased evaporation. The (black) water is out of the scale in this presentation. An interesting detail can be seen: the colour of the blossom's mirror-image is darker than the blossom itself in contrast to our optical experience. This phenomenon was discussed earlier in connection with thermographic investigations of the tropical water lily *Victoria cruziana* [25]. Briefly, colours in thermograms represent temperatures and thus energies emitted in the chosen wavelength. The radiation received by the camera consists of three components: the contribution from the reflecting object itself (water), from the reflected object (blossom), and from the atmosphere. The latter term can be neglected in most cases, so that the first two may be added taking their coefficients of emissivity and reflectivity into consideration. If the reflected body is warmer than the reflecting one, there is a shift to lower temperatures in the mirage as seen in Fig. 7. For further details see [25].

4. Discussion

Due to the usually small temperature differences between their surface and the environment plants are rather seldom investigated by thermography. Chaerle et al. could show with this method that locally defined tobacco mosaic virus infections produced spots of increased temperature on the leaves long before the onset of visible cell death [15–17]. They confirmed their assumption that salicylic acid, a signal of defence against pathogens in plants, induced an alternative, cyanide insensitive respiration as it does in thermogenic plants. Freezing is an important phenomenon in wild plants as well as crops. It is connected with an exothermic heat production visible in IR thermograms [18–21]. Most interesting for thermography are of course the so-called thermogenic plants with temperature differences of more than 10 K in inflorescences and special organs during their metabolic flare-up. Typical examples for this group were investigated by thermography, among them the voodoo lily *Sauromatum guttatum* [9,11,26], some other aroids [8,12,26], Philodendron (*Philodendron selloum*) [8] and the tropical water lily *Victoria cruziana* [25,26,33]. A short survey of plant thermography was published recently [22]. Most of the cited investigations were indoor experiments, not comparable with the results of the present strictly outdoor applications.

Interpreting plant thermograms one has to keep in mind that most plant structures are characterized by a large surface-to-volume ratio that influences their energy balances. This is composed by the absorbed solar radiation, the IR influx from the environment and perhaps the heat production by metabolic activities on the credit side. The debit amount counts the emitted IR radiation, heat convection, heat conduction and heat loss by evaporation [34]. As solar radiation is a significant input into the system, high cooling rates are to be expected when blossoms are experimentally shaded.

During the promenade many plants were observed that were intensively visited by insects, mainly by honeybees from nearby apiaries and bumblebees. The yellow blossoms of the Crown Daisy (*C. coronarum*), the Black-eyed Susan (*R. fulgida*), the Ox-eye Sunflower (*H. helianthoides*) and the common Sunflower (*H. annuus*) as well as some Dahlia were of special interest for the bees. Usual gifts for pollinating insects are nectar and pollen [35], but heat rewards are also known, especially for arctic and alpine flowers [30,31]. Although the mean body temperature of a honeybee is higher than the surface temperature of a blossom, the visit to a flower may be interesting due to sun basking and retarded heat loss. In many cases, the bowl-shaped form of the blossoms offers protection against wind and thus a special microclimate for the animal.

5. Conclusion

Chaerle and Van der Straaten published a paper entitled "Seeing is believing: imaging techniques to monitor plant health" that underlines the new facilities opened by thermography [16]: early detection of diseases of structural damages before they become visible to the eye. But "Seeing is believing" may be applied also in other fields of botany. Figs. 1 and 2 present contact-free temperature determinations in small blossoms, which would be difficult or impossible with classical methods. They give information about the influence of the blossom's shape on its ameliorated microclimate and thus about accelerated ripening of pollen and seeds and about energetic rewards for pollinating insects. The latter aspect may have been important during the evolution of thermogenic plants and their visitors and perhaps for the question why some flowers are of special interest for honeybees besides their colours in the optical and UV range and the high rewards of pollen and nectar.

In general, outdoor thermography is a promising new tool that should find more application in agriculture and horticulture [7] and should enter the botanic gardens after its successful conquest of the zoological ones.

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