Confirmation of the Structures of Lutein and Zeaxanthin

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A series of new esters of lutein (**1a**) have been prepared with the aim of confirming the structure of lutein *via* an X-ray crystal-structure analysis. Although well crystallized, only one of the derivatives, the (−)-(1*R*)-menthyl carbonate (**1i**) proved to be useful for a complete structure analysis. The same derivative of zeaxanthin (**2a**) also allowed its crystal structure to be determined. Both analyses represent the first successful X-ray crystal structure analyses of the most important xanthophylls. At the same time, they confirm both the constitution and absolute configuration of **1a** and **2a** that had been deduced earlier by classical methods.

1. Introduction. – Lutein (=(3*R*,3′*R*,6′*R*)-β,ε-carotene-3,3′-diol; **1a**), and zeaxanthin (=(3*R*,3′*R*)-β,β-carotene-3,3′-diol; **2a**) constitute an essential part of all chloroplasts of higher plants, and, therefore, may be regarded as the xanthophylls with a vital rôle for maintaining life on our earth. Both occur primarily in the light-harvesting complex (LHC) and there complement chlorophyll in converting visible light to useful energy [1][2], but beyond that they can be found in many other parts of plants, especially in yellow flowers and fruits.

Crystalline lutein, relatively free of isomers, was isolated for the first time in 1907 by *Willstätter* and *Mieg* from the leaves of stinging nettles (*Urtica urens*) [3] and shown by these authors by classical combustion analysis to have the formula $C_{40}H_{56}O_2$. Following an earlier proposal of *Berzelius*, *Willstätter* designated the new carotenoid as 'Xanthophyll', a term which was consequently used by *Karrer* in all of his relevant publications on this subject, although *Kuhn* had soon renamed it as 'Lutein' [4], admittedly on fairly weak arguments. This new term was quickly adopted, mainly by biologists, and so the term 'Xanthophyll' only survived as a group name for hydroxylated carotenoids.

After the isolation of lutein, more than 20 years elapsed before its constitution was elucidated, mainly through the work of *Karrer et al.* [5]. Again, more than 40 years later, intense efforts by the groups of *Weedon* (London), *Liaaen-Jensen* (Trondheim) and *Eugster* (Zürich) led to the absolute configuration of lutein as (3*R*,3′*R*,6′*R*) [6], which is now generally accepted. The most unexpected result of these investigations was the *trans*-orientation of the substituents at C(6′) and C(3′).

The first synthesis of optically-active lutein was achieved by *Mayer* and *Rüttimann* [7].

The unusual *trans*-orientation of the substituents at C(3′) and C(6′) caused several scientists to try to confirm or to disprove this situation by performing a crystal-structure

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analysis of lutein. The first known experiments on racemic models were tried by *Khatoon*, *Toube* and *Weedon* (cited by *Weedon* [8]) and with lutein (probably on the MeOH solvate) by *DeVille* and *Nathan*, cited by *Moss* [9], but without useful results. Independently, *Bieri* and *Prewo* of our institute tried hard in 1984 with a well crystallized lutein–MeOH solvate, but again with poor results [10].

To the best of our knowledge, a convincing crystal-structure analysis of lutein has not yet been published. Some of the intrinsic difficulties of such approaches are mentioned in the following paragraphs. We finally reached our goal of obtaining a reliable crystal-structure analysis when we turned to an investigation of a series of esters and other derivatives of lutein, but only one of them proved to be useful.

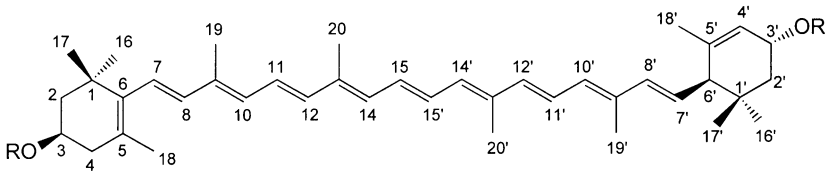
2. Derivatives of Lutein (1a). – Many years ago, a series of well-crystallized esters (and a few ethers), most of them of homologous fatty acids, were prepared by *Karrer* and *Ishikawa* [11]. Lately, we have prepared several of them again and subjected them to various crystallization procedures, such as variation of solvents, application of temperature gradients or diffusion methods, but without success. None of the crystals proved to be good enough for a crystal-structure analysis. Later on, we turned to esters and ethers with more space-demanding properties, *e.g.*, to pivalic acid (=2,2-dimethylpropanoic acid) or optically active camphanic acid [12], but again without success. Finally, the (−)-(1*R*)-menthyl carbonate (**1i**), prepared from lutein and (−)-(1*R*)-menthyl chloroformate, a reagent first described by *Westley* and *Halpern* for the gas-chromatographic separation of racemic amines and alcohols [13], gave crystals good enough for a complete crystal-structure determination (see *Sect. 6*). Some of the new derivatives, which were fully characterized spectroscopically, like the bis(formate) **1b**, bis(acetate) **1c**, bis[chloroacetate] **1d**, the dimethylether **1e**, the bis(pivaloate) **1f**, the bis[(−)-camphanoate] **1g**, the bis[methyl carbonate] **1h**, and the bis[menthyl carbonate] **1i** are described in the *Exper. Part* (see *Scheme*).

3. Zeaxanthin. – Zeaxanthin (=(3*R*,3*R*′)-*β*,*β*-carotene-3,3′-diol; **2a**) was first isolated by *Karrer et al.* [5], and named according its occurrence in yellow corn (*Zea mays*). The elucidation of the constitution of zeaxanthin was conducted parallel to that of lutein [5][14]. Around the same time, crystalline physalien was isolated from calyces of *Physalis alkekengi* [15], but only later recognized as being the palmitic ester of zeaxanthin [16][17].

The constitution of zeaxanthin was elucidated around 1930, again by *Karrer et al.*, by classical degradation methods and mostly parallel to that of lutein [5][14]. A first synthesis of zeaxanthin, probably a mixture of *rac*- and *meso*-forms, was published by *Isler et al.* in 1956 [18]. Twenty years later, the absolute configuration of natural zeaxanthin was determined by *Weedon* and co-workers [19], and, a few years later, in a remarkable effort, several synthetic routes to optically active (natural) zeaxanthin were described by chemists of *F. Hoffmann-La Roche* [20]. However, no crystal structure of zeaxanthin has been published so far.

In our hands, the (−)-(1*R*)-menthyl chloroformate again yielded a well crystallized bis[menthyl carbonate] **2b**, which proved to be suitable for crystallographic analysis (see *Sect. 6*).

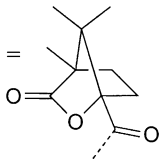
Scheme

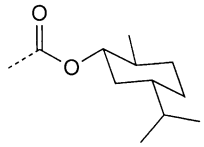


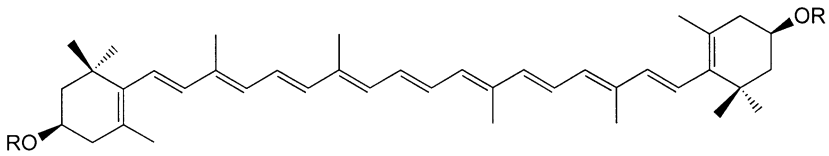
1a R = H **1b** R = CHO

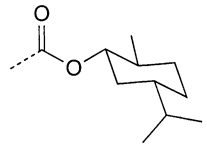
1c R = Ac **1d** R = $ClCH_2CO$

1e R = Me **1f** R = *t*-BuCO

1g R =  **1h** R = MeOCO

1i R = 



2a R = H **2b** R = 

4. Acylation Procedures. – Our acylation procedures followed no standard method, as, according to the specific character of the activated acids used, mixtures of the mono- and bis-esters were always obtained together with some starting material, even when the reagents were applied in excess. Modifications in the nature of the solvents and the reaction temperature were necessary to improve the yield (see *Exper. Part*).

5. Simplified Procedure to Obtain Substantial Amounts of Pure Lutein. – To provide a good supply of relatively pure lutein for all experiments, we have worked out a simple laboratory procedure that starts with a concentrate of lutein obtained from the flowers of *Tagetes*, (the so-called 'marigold oleoresin'). It allows the preparation of *ca.* 12 g of crystalline, solvent-free lutein pro batch of 100 g of dry oleoresin, with a purity

of 93%. It is contaminated with zeaxanthin and kryptoxanthin, which can only be removed by more elaborate chromatographic procedures.

6. The Crystal Structures of 1i and 2b. – Views of the molecules of **1i** and **2b** are shown in *Fig. 1*, *a* and *b*, respectively. For **1i**, the menthyl group at one end of the molecule is disordered over two slightly different conformations. Only the major conformation is shown in the *Figs.* The compounds do not contain elements with significant anomalous scattering power, which means that the absolute configuration of each compound could not be determined independently by the diffraction experiment. However, the presence of moieties of known absolute configuration in the molecules, namely the (1*R*)-menthyl carbonate substituents at the 3,3′-positions, which did not change their configuration during the syntheses of **1i** and **2b**, were used to choose the enantiomorph used in the structure-refinement model. Thus, the absolute configuration of the carotene moieties could be confirmed, relative to these known chiral centres, for the first time and were found to agree with those predicted from other experiments [6][19]. The configuration of the polyene side-chain in each compound is (all-*E*).

6.1. *Conformation of the Polyene Side Chain.* The pattern of bond lengths within the polyene chains of **1i** and **2b** corresponds with that normally observed for highly conjugated compounds of this type. For **1i**, the formal C=C bonds are in the range 1.337(4) – 1.373(5) Å, and the intermediate formal single bonds are in the range 1.429(5) – 1.495(5) Å. For **2b**, the corresponding ranges are 1.321(6) – 1.366(6) Å and 1.425(5) – 1.473(7) Å, respectively (*Table 1*). These ranges encompass a trend towards a slight lengthening of the C=C bonds and shortening of the single bonds closer to the middle of the chain. This property has been observed in related compounds and is attributed to the increased delocalization of the π-bonds in the middle of the chain [21].

Each end of the conjugated polyene chains shows the typical sabre-like, in-plane bending observed for retinals and carotenoid compounds [21 – 23]. The chain angles for an unhindered conjugated chain are *ca.* 125° [24]. In **1i** and **2b**, the angles opposite the Me substituents are compressed to 119 – 121° and 118 – 120°, respectively, while the chain angles adjacent to the substituents are in the range 124 – 128° and 126 – 129°, respectively (*Table 1*). This effect is essentially the result of non-bonded interactions between the Me substituents on the chain and adjacent H-atoms. *Schenk* [22] defined an expression for the bending in sections of dimethyl-substituted polyene chains as $\Delta = a - b + c - d + e - f$, where the angles *a* to *f* are the chain angles associated with the atoms C(8) to C(13), or C(28) to C(33), respectively (see structural formula of **1i** and *Fig. 1*). For the two sections of this kind in **1i**, the values of Δ are 8.8° and 10.2°, respectively, while for **2b**, they are 21.5° and 19.5°, respectively. The values for **2b** are similar to those calculated from the structures of related (all-*E*)-polyenes, while those for **1i** show less pronounced in-plane bending. In each compound, the direction of the sabre-like bend at one end of the polyene chain is reversed at the other end of the chain, thereby leading to an overall shallow in-plane wave pattern along the entire length of the polyene chain.

The conjugated chains of both compounds are not completely planar, as shown by the torsion angles about the bonds within the chain (*Table 2*). These deviations from planarity are caused by small twists about the bonds, with the maximum twist about any one bond being 13.3(4)° in **1i** and 7.8(5)° in **2b**. Interestingly, this maximum twist occurs

Table 1. *Selected Bond Lengths* [Å] *and Angles* [°] *for the Structures of* **1i** *and* **2b**, *with Standard Uncertainties in Parentheses*

	1i	**2b**
C(4)–C(5)	1.505(5)	1.519(7)
C(5)–C(6)	1.350(5)	1.352(6)
C(6)–C(7)	1.478(5)	1.473(7)
C(7)–C(8)	1.337(4)	1.335(6)
C(8)–C(9)	1.452(5)	1.467(6)
C(9)–C(10)	1.366(4)	1.335(6)
C(10)–C(11)	1.431(5)	1.453(7)
C(11)–C(12)	1.358(4)	1.327(6)
C(12)–C(13)	1.448(5)	1.452(7)
C(13)–C(14)	1.366(4)	1.351(7)
C(14)–C(15)	1.432(5)	1.425(7)
C(15)–C(35)	1.358(4)	1.341(6)
C(24)–C(25)	1.342(5)	1.512(6)
C(25)–C(26)	1.511(5)	1.335(6)
C(26)–C(27)	1.495(5)	1.468(7)
C(27)–C(28)	1.340(5)	1.321(6)
C(28)–C(29)	1.451(5)	1.453(6)
C(29)–C(30)	1.359(5)	1.358(7)
C(30)–C(31)	1.434(5)	1.435(7)
C(31)–C(32)	1.350(5)	1.355(7)
C(32)–C(33)	1.432(5)	1.445(7)
C(33)–C(34)	1.373(5)	1.366(6)
C(34)–C(35)	1.429(5)	1.427(6)
C(6)–C(7)–C(8)	127.9(3)	129.1(5)
C(7)–C(8)–C(9)	124.7(3)	126.1(5)
C(8)–C(9)–C(10)	120.7(3)	118.2(4)
C(9)–C(10)–C(11)	125.4(3)	128.7(5)
C(10)–C(11)–C(12)	125.6(3)	123.5(5)
C(11)–C(12)–C(13)	124.4(3)	126.8(5)
C(12)–C(13)–C(14)	119.4(3)	118.4(5)
C(13)–C(14)–C(15)	127.5(3)	128.9(5)
C(14)–C(15)–C(35)	124.2(3)	124.0(5)
C(26)–C(27)–C(28)	125.4(3)	126.7(5)
C(27)–C(28)–C(29)	125.4(4)	127.9(5)
C(28)–C(29)–C(30)	120.7(3)	119.5(4)
C(29)–C(30)–C(31)	125.6(3)	127.9(5)
C(30)–C(31)–C(32)	126.3(3)	124.0(5)
C(31)–C(32)–C(33)	126.1(3)	125.9(5)
C(32)–C(33)–C(34)	119.9(3)	118.7(5)
C(33)–C(34)–C(35)	127.2(3)	127.8(5)
C(15)–C(35)–C(34)	124.1(3)	124.6(5)

about the same bond, C(28)–C(29), in both compounds. Contrary to the usual observations, some of the largest twists occur about the C=C bonds. *Table 3* shows the successively increasing angles between the four-atom planes along the chain and the plane defined by the atoms C(6)–C(7)–C(8)–C(9). Twists about the chain bonds can lead to both an out-of-plane bending and a longitudinal twisting of the chain. In **1i**, both ends of the polyene chain display significant out-of-plane curvature with respect to the center of the chain, but in the opposite sense, so that the overall polyene chain, when

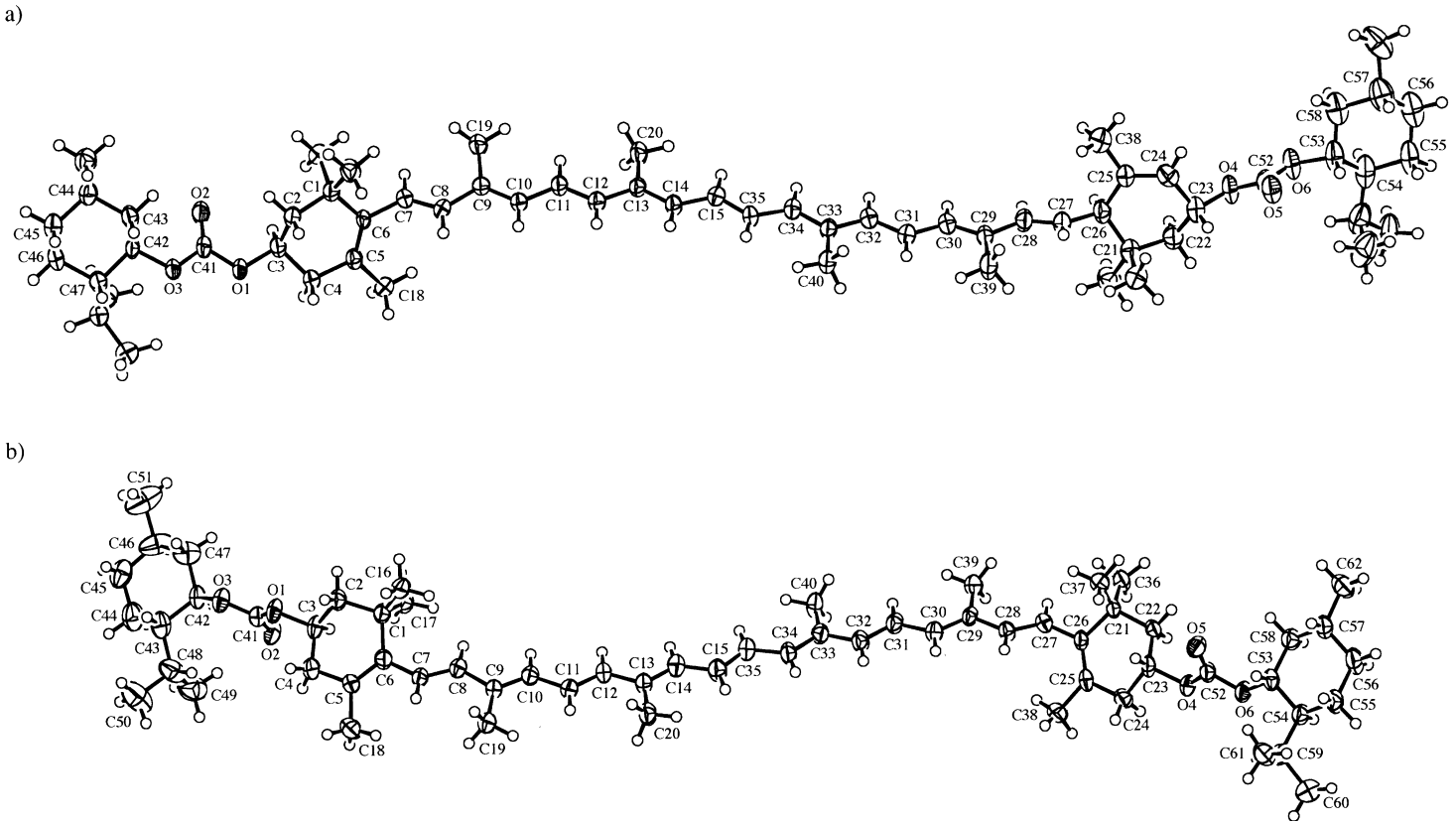


Fig. 1. *The molecular structures of* a) **1i** *and* b) **2b** (50% probability ellipsoids; only the the major conformation of the disordered menthyl carbonate group in **1i** is shown)

viewed from the side, has a shallow wave form with slight twists at the ends (*Fig. 2,a*). The same effect is observed in **2b** (*Fig. 2,b*), but to a lesser extent so that the entire chain looks more planar than that of **1i**. Out-of-plane bending has been noted for related carotenoid and retinal compounds, and is thought to be caused by intermolecular forces [24a][25–27].

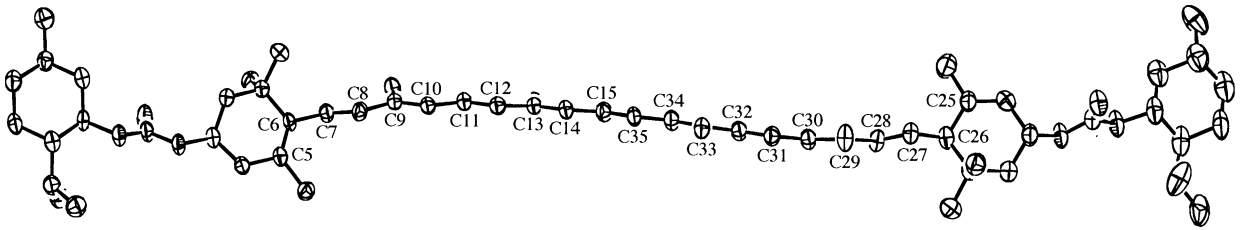
Table 2. *Selected Torsion Angles* [°] *for* **1i** *and* **2b**, *with Standard Uncertainties in Parentheses*

	1i	**2b**
C(5)–C(6)–C(7)–C(8)	–68.8(5)	144.5(6)
C(1)–C(6)–C(7)–C(8)	115.2(4)	–36.4(8)
C(6)–C(7)–C(8)–C(9)	–178.7(3)	–177.0(5)
C(7)–C(8)–C(9)–C(10)	–171.8(3)	–178.1(5)
C(8)–C(9)–C(10)–C(11)	171.7(3)	175.5(5)
C(9)–C(10)–C(11)–C(12)	–178.9(3)	179.6(5)
C(10)–C(11)–C(12)–C(13)	172.2(3)	177.8(5)
C(11)–C(12)–C(13)–C(14)	178.5(3)	176.6(5)
C(12)–C(13)–C(14)–C(15)	177.7(3)	179.2(5)
C(13)–C(14)–C(15)–C(35)	–177.9(3)	–177.1(6)
C(25)–C(26)–C(27)–C(28)	118.0(4)	48.5(8)
C(21)–C(26)–C(27)–C(28)	–114.3(4)	–132.4(5)
C(26)–C(27)–C(28)–C(29)	174.4(3)	–177.9(5)
C(27)–C(28)–C(29)–C(30)	166.7(4)	172.2(5)
C(28)–C(29)–C(30)–C(31)	–176.3(3)	–174.5(5)
C(29)–C(30)–C(31)–C(32)	170.0(4)	178.1(5)
C(30)–C(31)–C(32)–C(33)	–177.9(3)	179.5(5)
C(31)–C(32)–C(33)–C(34)	178.8(3)	–177.5(5)
C(32)–C(33)–C(34)–C(35)	178.1(3)	178.6(5)
C(14)–C(15)–C(35)–C(34)	176.8(3)	178.3(5)
C(33)–C(34)–C(35)–C(15)	–178.3(3)	179.4(5)

Table 3. *Angles* [°] *between Four-Atom Planes of the Polyene Chain and the C(6)–C(7)–C(8)–C(9) Plane of* **1i** *and* **2b**

Plane	**1i**	**2b**
C(7)–C(8)–C(9)–C(10)	5.1(7)	2.3(7)
C(8)–C(9)–C(10)–C(11)	7.7(7)	2.5(7)
C(9)–C(10)–C(11)–C(12)	8.1(7)	2.9(8)
C(10)–C(11)–C(12)–C(13)	10.5(7)	3.8(8)
C(11)–C(12)–C(13)–C(14)	13.3(7)	6.4(7)
C(12)–C(13)–C(14)–C(15)	14.0(7)	7.3(8)
C(13)–C(14)–C(15)–C(35)	15.0(7)	6.3(8)
C(14)–C(15)–C(35)–C(34)	16.3(7)	6.4(8)
C(26)–C(27)–C(28)–C(29)	28.2(7)	8.2(8)
C(27)–C(28)–C(29)–C(30)	19.2(7)	4.6(7)
C(28)–C(29)–C(30)–C(31)	18.3(7)	5.8(7)
C(29)–C(30)–C(31)–C(32)	18.6(7)	8.7(8)
C(30)–C(31)–C(32)–C(33)	18.4(7)	8.2(8)
C(31)–C(32)–C(33)–C(34)	19.1(7)	8.8(8)
C(32)–C(33)–C(34)–C(35)	18.5(7)	8.6(8)
C(33)–C(34)–C(35)–C(15)	17.7(7)	7.4(8)

a)



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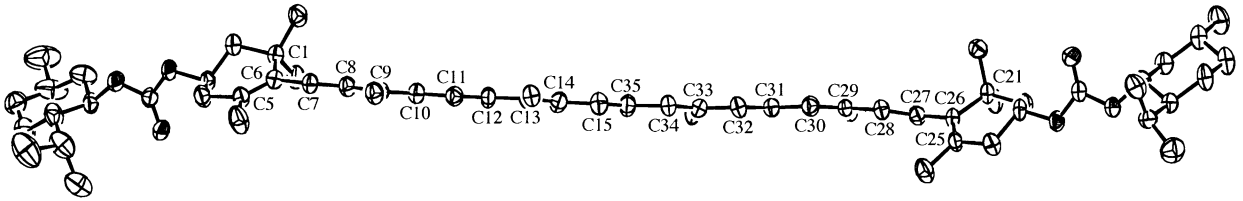

Fig. 2. *The structures of* a) **1i** *and* b) **2b** *viewed in the plane of the polyene chain* (50% probability ellipsoids; H-atoms omitted for clarity; only the the major conformation of the disordered menthyl carbonate group in **1i** is shown)

When the menthyl carbonate substituents and the cyclohexene rings are taken into consideration, the entire form of the molecule in each compound differs significantly, as shown by the packing diagrams in *Figs. 3* and *4*. The molecule of **1i** retains quite a linear conformation, while significant curvature is observed for **2b**, which lends the molecule a striking 'S-shaped' conformation.

Fig. 3. *The crystal packing of* **1i** *viewed down the* a-*axis* (only the the major conformation of the disordered menthyl carbonate group is shown)

6.2. *Conformations of the Cyclohexene Rings.* The bond lengths and angles of the cyclohexene rings exhibit the normally expected values. The conformation of the cylohex-5-ene ring in **1i** is that of a C(2),C(3)-half chair with atoms C(2) and C(3) on opposite sides of the plane through atoms C(1), C(6), C(5), and C(4). The deviations from this plane for C(2) and C(3) are −0.267(4) and 0.475(4) Å, respectively. The substituents at C(3) and C(6) occupy equatorial positions. The cyclohex-4-ene ring has a C(21),C(22)-half-chair conformation with atoms C(21) and C(22) on opposite sides of the plane through atoms C(23), C(26), C(25), and C(24). The deviations from this plane for C(21) and C(22) are −0.387(4) and 0.350(3) Å, respectively, and the substituents at C(23) and C(26) also occupy equatorial positions. Similarly, the conformation of each cylohex-5-ene ring in **2b** is that of a C(2),C(3)-half chair. The deviations of atoms C(2) and C(3) from the plane defined by atoms C(1), C(6), C(5), and C(4) are −0.446(5) and 0.328(5) Å, respectively, while the deviations of atoms C(22) and C(23) from the plane defined by atoms C(21), C(26), C(25), and C(24) are −0.294(5) and 0.444(5) Å, respectively. The substituents at C(3) and C(6), and at C(23) and C(26) occupy equatorial positions.

6.3. *Torsion Angles about the C(6)–C(7) Bond.* One purpose of the investigation of the structures of **1i** and **2b** was to determine the C(5)–C(6)–C(7)–C(8) torsion angle, ω_1 (*Fig. 5*), since the shapes of the CD spectra of this class of compounds are known to be sensitive to ω_1. For **1i** and **2b**, this torsion angle is −68.8(5)° and 144.5(6)° respectively. In **2b**, the corresponding torsion angle in the second cyclohex-5-ene ring is also relevant, and the C(25)–C(26)–C(27)–C(28) torsion angle is 48.5(8)°.

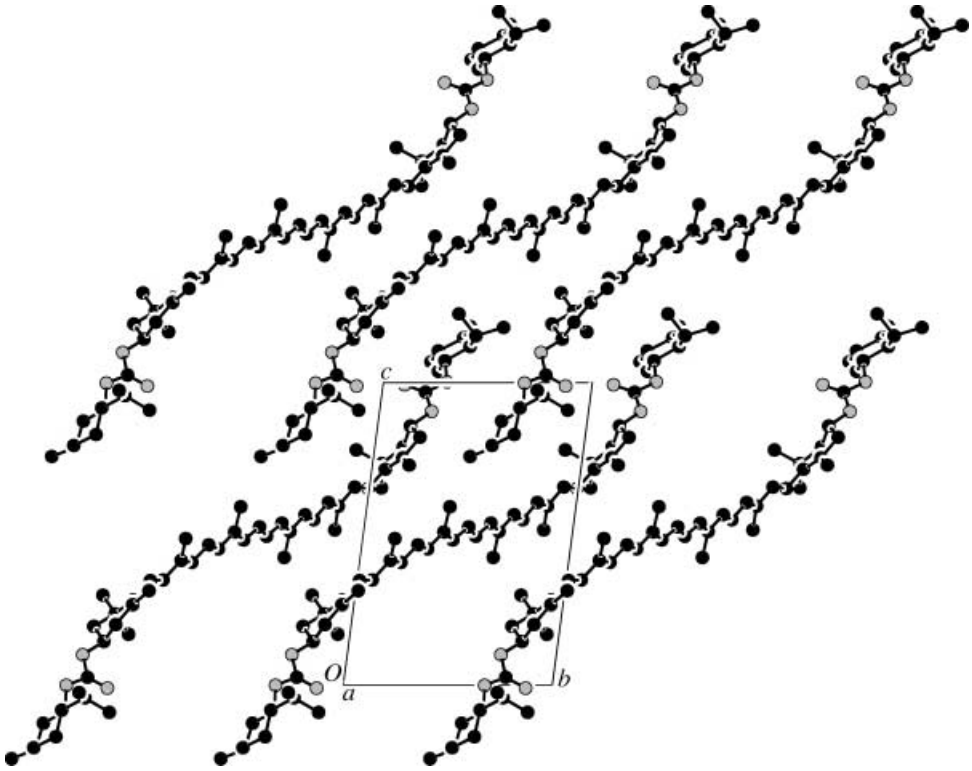

Fig. 4. *The crystal packing of* **2b** *viewed down the* a-*axis*

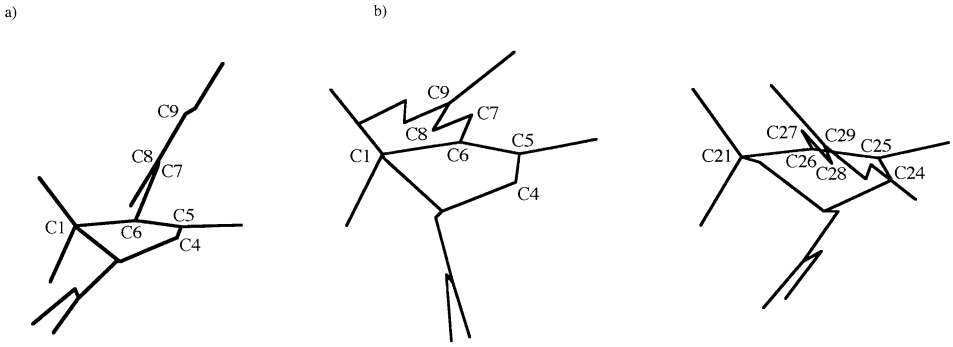

Fig. 5. *Views of the torsion angle,* ω_1*, between the* π *systems of the polyene chain and the cyclohex-5-ene rings* (β-*rings*) *in* a) **1i** *and* b) *the two chemically equivalent ends of* **2b** (only the atoms in the immediate vicinity of the ring are shown)

The large differences for these torsion angles between not only lutein ester **1i** and zeaxanthin ester **2b**, but also between the chemically equivalent β-end groups of **2b** are unexpected and remain unexplained. They may be caused by crystal packing, because the CD spectra of **1i** and **2b** are very much like those of their parent compounds, and,

further, published temperature-dependent spectra of zeaxanthin do not indicate any significant modification of the shape of the curve [28], except for a substantial increase in the intensity of the $\Delta\varepsilon$ values. Probably, the esters **1i** and **2b** in solution adapt an average value of ω_1 whose magnitude remains unknown. Based on the theoretical model, *Buchecker* and *Noack* determined a value of *ca.* 40° for ω_1 of zeaxanthin [28].

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Experimental Part

General. See [29]. Signals in the ^{13}C-NMR spectra are not completely assigned, and some of the assignments especially in the olefinic region may need interchange (*).

1. *Isolation of Lutein* (**1a**) *from an Extract of Dried flowers of* Tagetes erecta (*Marigold oleoresin*). A brownish-orange powder (100 g), containing 10–18% lutein, was mixed with fine quarz-sand and *Celite*, and covered with 2 l of CH_2Cl_2/AcOEt 1:1 and stirred for 24 h at r.t. After filtering and pouring the extract on a well-settled column of 2 kg of silica gel (*Merck 60*, 0.004–0.063 mm, filled as a degassed slurry), followed by progressive elution of the individual carotenoids with a solvent consisting of CH_2Cl_2/AcOEt/i-PrOH/EtN(i-Pr)$_2$ 47:47:1.5:0.5, the dark reddish-brown lutein fraction was slowly eluted from a large blackish-red zone, which remained on the column. Yield: 40 g of a red partial solid. After dissolution in 400 ml of boiling MeOH with the help of a little benzene and storing overnight at +5°, the crystals were separated and dried *in vacuo*. Yield: 13.9 g of glistening dark red crystals of a lutein-MeOH-solvate. Recrystallisation from hot THF with addition of methylcyclohexane yielded **1a** as blackish-red crystals with a coppery hue (purity 93% by HPLC and UV/VIS analysis).

2. *Lutein-3,3′-diyl Diformate* (**1b**). In a small three-necked round-bottom flask provided with a magnetic stirrer, a septum and an inlet for Ar, 650 mg of **1a** were dissolved in 6 ml of abs. THF. After chilling to 0°, a reagent of 1.5 ml of FAM (HCOH/Ac_2O mixture) prepared according to [30] was slowly added through a syringe. Finally, a few crystals of 4-(dimethylamino)pyridine were added. After stirring for 50 min, the solvent was removed *in vacuo*, and the solid residue was recrystallized at r.t. from CH_2Cl_2/(i-Pr)$_2$O to get red crystals, which were dried *in vacuo:* 515 mg (72%) of **1b** (sensitive to light, heat and protic solvents). Red crystals. M.p. (*in vacuo*) 112.5–113°. UV/VIS (CH_2Cl_2): λ_{max} 281.5 (log ε 4.37), 430.7 (4.95), 454.5 (5.12), 483.7 (5.07). CD (CH_2Cl_2): λ_{max} 245.6 ($\Delta\varepsilon$ 6.60), 286.6 (−2.21), 337.2 (+0.69). IR (CH_2Cl_2, strong bands): 2963, 2927, 1718, 1187, 971. ^{1}H-NMR (600 MHz, CD_2Cl_2): 0.899 (*s*, Me(17′)); 1.015 (*s*, Me(16′)); 1.089 (*s*, Me(16)); 1.120 (*s*, Me(17)); 1.489 (*dd*, *J* = 17, 5.1, H$_{ax}$–C(2′)); 1.627 (*t*, *J* = 12.0, H$_{ax}$–C(2)); 1.844 (*m*, *J* = 12.3, H$_{eq}$–C(2)); 1.665 (*s*, Me(18′)); 1.737 (*s*, Me(18)); 1.875 (*dd*, *J* = 14.0, 6.1, H$_{eq}$–C(2′)); 1.911 (*s*, Me(19′)); 1.976 (*s*, Me(19,20,20′)); 2.178 (*dd*, *J* = 16.4, 9.6, H$_{ax}$–C(4)); 2.43 (*m*, H–C(6)); 2.45 (*dd*?, H$_{eq}$–C(4)); 5.17 (*m*, H$_{eq}$–C(3)); 5.44 (br. *s*, H$_{eq}$–C(3′)); *ca.* 5.46 (*dd*?, H–C(4), H–C(7′,?)); 6.2–6.7 (*m*, H–C(8,8′10,10′,11,11′)); 6.272 (*m*, H–C(14,14′)); 6.375 (*m*, H–C(12,12′)); 6.675 (*m*, H–C(15,15′)); 8.057 (CHO). ^{13}C-NMR (150 MHz, CD_2Cl_2): 13.05 (Me(19)); 13.14 (Me(20,20′)); 13.40 (Me(19′)); 21.80 (Me(18)); 23.21 (Me(18′)); 25.89 (Me(17′)); 28.83 (Me(17)); 29.20 (Me(16′)); 30.34 (Me(16)); 33.83 (C(1′)); 37.27 (C(1)); 38.92 (C(4)); 39.76 (C(2′)); 44.55 (C(2)); 55.48 (C(6′)); 68.92 (C(3)); 69.21 (C(3′)); 119.90 (C(4′)); *ca.* 126 (C(11,11′)); 126.04 (C(5)); *ca.* 129 (C(7′)); 130.15 (C(15,15′)); 131.51 (C(10′)); *ca.* 132 (C(10)); 133.15 (C(14,14′)); *ca.* 136.4 (C(9,9′)); 138.11 (C(6,12)); 139.3 (C(8′,12′)); *ca.* 141.76 (C(5′)); 161.30, 161.45 (C=O). EI-MS: 525 ($M^{+\bullet}$).

3. *Lutein-3,3′-diyl Diacetate* (**1c**). In the same apparatus as in *Exper. 2*, 2 ml of freshly distilled Ac_2O were added dropwise to a soln. of 163 mg of **1a** in 6 ml of pyridine and a few crystals of 4-(dimethylamino)pyridine at 0°. After stirring for 12 h at r.t., the solvents were removed *in vacuo*, and the crystalline residue was chromatographed on a column of silica gel with CH_2Cl_2/AcOEt/hexane 3:3:4. From the red main fraction, a solid was isolated and crystallized from AcOEt/MeOH: 115 mg (62%) of **1c**. Fine red crystals. (Solns. of **1c** proved to be less stable than those of **1a**). M.p. (*in vacuo*) 172° ([25]: 170°). UV/VIS (CH_2Cl_2): 271.6 (4.29), 430.9 (4.86), 455.0 (5.04), 484.5 (5.00). CD (CH_2Cl_2): 246.0 (5.65), 286.2 (−2.47), 337.0 (0.96). IR (KBr): 2964, 2921, 2863, 1733, 1365, 1244, 1024, 962. ^{1}H-NMR (600 MHz, $CDCl_3$): 0.887 (*s*, Me(17′)); 1.011 (*s*, Me(16′)); 1.087 (*s*, (Me(16)*); 1.118 (*s*, Me(17)*); 1.465 (*dd*, *J* = 13.8, 5.5, H$_{ax}$–C(2′)); 1.594 (*t*, *J* = 11.9, H$_{ax}$–C(2)); 1.659 (*s*, Me(18′)); 1.733 (*s*, Me(18)); 1.789 (*d*, *J* = 12.1, H$_{eq}$–C(2)); 1.853 (*dd*, *J* = 13.1, 6.8, H$_{eq}$–C(2′)); 1.916 (*s*, Me(19′));

1.975 (*s*, (Me(19,20)); 1.982 (*s*, (Me(20′)); 2.050 (*s*, AcO–C(3)); 2.058 (*s*, (AcO–C(3′)); 2.122 (*dd*, *J* = 15.9, 9.7, H_{ax}–C(4)); 2.417 (*d*, *J* = 9.7, H–C(6′)); 2.456 (*dd*, *J* = 17.1, 5.7, H_{eq}–C(4)); 5.501 (*m*, H–C(4′)); 5.07 (*m*, H_{eq}–C(3)); 5.34 (*m*, H_{eq}–C(3′)); 5.441 (*d*, *J* = 15.5, 9.7, H–C(7′)); *ca.* 6.15 (*m*, H–C(7,8,8′,10,10′)); *ca.* 6.63 (*m*, H–C(11,11′,12,12′,14,14′,15,15′)). ^{13}C-NMR (150 MHz, $CDCl_3$): 12.71 (Me(19)); 12.77 (Me(20,20′)); 13.07 (Me(19′)); 21.44 (Me(18)); 22.94 (Me(18′)); 25.26 (Me(17′)); 28.49 (Me(17)); 28.94 (Me(16′)); 29.97 (Me(16)); 33.42 (C(1′)); 38.44 (C(1)); 39.56 (C(4)); 44.03 (C(2)); 54.89 (C(6′)); 68.39 (C(3)); 68.83 (C(3′)); 119.95 (C(4′)); 124.74 (C(11′)); 124.87 C(11)); 125.26 (C(7)); 125.59 (C(5)); 128.28 (C(7′)); 130.07 (C(15,15′)); 130.94 (C(10′)); 131.40 (C(10)); 132.58 (C(14,14′)); 134.97 (C(9′)); 135.55 (C(9)); 136.44 (C(12′)); 137.62 (C(12)); 137.83 (C(6)); 138.63 (C(8)); 140.41 (C(5′)); 170.74, 170.83 (AcO).

4. *Lutein-3,3′-diyl Bis(2-chloroacetate)* (**1d**). In the same equipment as in *Exper. 2*, a soln. of 657 mg of **1a** in 10 ml of THF and 5 ml of pyridine was treated at r.t. dropwise with AcCl until **1a** disappeared (TLC). The solvents were then evaporated *in vacuo*, followed by extraction of the carotenoids with Et_2O, and thorough washing with H_2O and brine, and drying (Na_2SO_4). Chromatography on a column of silica gel (*Merck 60*, as before), degassed and filled as a slurry, and development with ligroin/AcOEt 9 : 1 yielded a crystalline, red residue. Recrystallization from THF/heptane gave **1d** (625 mg, 75%). Shining red crystals. M.p. (*in vacuo*) 178°. UV/VIS (CH_2Cl_2): 272.0 (4.28), 430.8 (4.86), 455.0 (5.03), 484.4 (4.99). CD (CH_2Cl_2): 245.6 (6.17), 285.2 (–2.68), 341.2 (1.31). IR (KBr): 2961, 2922, 2858, 1757, 1192, 1167, 964. ^{1}H-NMR (500 MHz, $CDCl_3$): 0.885 (*s*, Me(17′)); 1.015 (*s*, Me(16′)); 1.086* (*s*, Me(16)); 1.113* (*s*, Me(17)); 1.502 (*dd*, *J* = 14.1, 4.7, H_{ax}–C(2′)); *ca.* 1.64 (H_{eq}–C(2′)); 1.667 (*s*, Me(18′)); 1.729 (*s*, Me(18)); 1.83 (*dd*, *J* = ?, H_{ax}–C(2)); 1.88 (*dd*, *J* = ?, H_{eq}–C(2′)); 1.902 (*s*, Me(19′)); 1.966 (*s*, Me(19,19′,20,20′)); 2.405 (*d*, *J* = 9.3, H–C(6′)); *ca.* 2.47 (*dd*-like, *J* = ?, H_{eq}–C(4)); 4.036, 4.050 (2*s*, CH_2Cl); *ca.* 5.1 (*m*, H–C(3)); 5.41 (*m*, H–C(3′,7′)); *ca.* 6.06–6.3 (*m*, H–C(7,8,8′,10,10′)); *ca.* 6.26 (*dd*-like, *J* = ?, H–C(14,14′)); *ca.* 6.36 (*dd*, *J* = 15.0, 5.0, H–C(12,12′)); *ca.* 6.62 (*m*, H–C(11,11′,15,15′)). Anal. calc. for $C_{44}H_{58}Cl_2O_4$ (721.85): C 73.21, H 8.10, Cl 9.82; found: C 73.03/73.06, H 8.18/8.25, Cl 9.38/9.69.

5. *3,3′-Dimethoxylutein* (**1e**; simplified and improved procedure according to [31]). In the same equipment as in *Exper. 2*, 203 mg of **1a** were dissolved in 10 ml of benzene. After addition of 160 mg of *t*-BuOK, the soln. was warmed to 35°. The potassium salt of **1a** soon precipitated. After addition of 4 ml MeI, the precipitate slowly disappeared. The mixture was stirred at the same temp. for 12 h. Then, evaporation of the solvents *in vacuo*, followed by extraction of the colored compounds and purification by chromatography on silica gel (as described before) with benzene/AcOEt 4 : 1 yielded from the brownish-red main fraction 153 mg (73%; [31]: 6%) of **1e**. Red crystals from Et_2O/hexane. M.p. (*in vacuo*): 164° ([31]: 155°). UV/VIS: 271.3 (4.36), 432.0 (4.94), 455.0 (5.11), 484.1 (5.07). CD (CH_2Cl_2): 229.0 ($\Delta\varepsilon$ 2.14), 247.5 (5.13), 289.0 (–1.96). IR ($CHCl_3$): 2964, 2926, 1089, 970). ^{1}H-NMR (600 MHz, $CDCl_3$): 0.844 (*s*, Me(17′)); 0.973 (*s*, Me(16′)); 1.074 (*s*, Me(16,17)); 1.394 (*d*, *J* = 11.9, H_{ax}–C(2′)); 1.411 (*dd*, *J* = 12.4, 3.3, H_{ax}–C(2)); 1.567 (?); 1.622 (*s*, Me (18′)); 1.739 (*s*, Me(18)); 1.766 (*dd*, *J* = 5.9, 5.8, H_{eq}–C(2′)); 1.831 (*d*-like, *J* = 12.2, H_{eq}–C(2)); 1.911 (*s*, Me(19′)); 1.966 (*s*, Me(20,20′); 1.973 (*s*, Me(19)); 2.01 (*dd*, *J* = 16.9, 9.6, H_{ax}–C(4)); *ca.* 2.42 (*m*, H–C(6′), H_{eq}–C(4)); 3.365 (*s*, MeO–C(3′)); 3.381 (*s*, MeO–C(3)); *ca.* 3.51 (*m*, H–C(3)); *ca.* 3.78 (*m*, H–C(3′)); 5.441 (*dd*, *J* = 10.0, 9.9, H–C(7′)); 5.601 (‘*s*’, H–C(4′)); *ca.* 6.15 (*m*, H–C(7,8′,10,10′)); 6.252 (*d*-like, H–C(14,14′)); 6.502 (*dd*, *J* = 6.3, H–C(12,12′)). ^{13}C-NMR (150 MHz, $CDCl_3$): 12.75 (Me(19)); 12.81 (Me(20,20′)); 13.11 (Me(19′)); 21.70 (Me(18)); 22.95 (Me(18′)); 24.29 (Me(17′)); 28.69 (Me(16)); 29.45 (Me(16′)); 30.26 (Me(17)); 33.89 (C(1′)); 36.71 (C(1)); 39.28 (C(4)); 40.42 (C(2′)); 44.54 (C(2)); 55.15 (C(6′)); 55.58 (MeO–C(3′)); 55.78 (MeO–C(3)); 73.67 (C(3)); 74.60 (C(3′)); 121.89 (C(4′)); 124.84 (C(11′)*); 124.95 (C(11)*); 125.72 (C(7)); 126.12 (C(5)); 128.98 (C(7′)); 130.03 (C(15)); 130.07 (C(15′)); 130.72 (C(10)); 131.25 (C(10′)); 132.54 (C14,14′)); 135.73 (C(9,9′)); 136.41 (C(13′)); 136.48 (C(13)); 137.58 (C(12,12′)); 137.64 (C(8′)); 137.85 (C(5′)); 138.21 (C(6)); 138.3 (C(8)). CI-MS: 597 (96, $M^{+\bullet}$), 565 (20, $[M - MeO]^{+\bullet}$).

6. *Lutein-3,3′-diyl Bis(2,2-dimethylpropanoate)* (**1f**). In the same equipment as in *Exper. 2*, a soln. of 188 mg of **1a** in 6 ml of THF and 4 ml of pyridine was treated at 50° intermittently with small droplets of pivaloyl chloride until **1a** disappeared (TLC). Usual workup with Et_2O, H_2O and brine yielded a redish residue, which was chromatographed on a column of silica gel (as described before). From the deep red main fraction 200 mg of crystalline **1f** were isolated. Recrystallisation from benzene/MeOH yielded red glittering thin leaflets. M.p. (*in vacuo*) 202–203°. UV/VIS (CH_2Cl_2): 270.5 (4.38), 455.1 (5.13), 484.3 (5.08). CD (CH_2Cl_2): 245.8 (8.58), 285.0 (–4.31), 343.6 (1.76), 455.2 (with fine structure; 3.61). IR ($CHCl_3$, strong bands): 2967, 1784, 1741, 1721, 1275, 1171, 1107, 1063, 969. ^{1}H-NMR (600 MHz, $CDCl_3$): 0.887 (*s*, Me(17′)); 1.035 (*s*, Me(16′)); 1.090 (*s*, Me(16)); 1.125 (Me(17)); 1.201, 1.209 (2*s*, *t*-Bu); 1.265 (?); 1.403 (*dd*, *J* = 16.1, 4.2, H_{ax}–C(2′)); 1.579 (*t*, *J* = 11.9, H_{ax}–C(2)); 1.668 (*s*, Me(18′)); 1.735 (*s*, Me(18)); 1.781 (*d* with fine structure, H_{eq}–C(2)); 1.839 (*dd*, *J* = 14.1, 5.9, H_{eq}–C(2′)); 1.915 (*s*, Me(19′)); 1.977 (*s*, Me(20,20′)); 1.982 (*s*, Me(19)); 2.108 (*dd*, *J* = 15.7, 9.3, H_{ax}–C(4)); 2.378 (*d*, *J* = 9.5, H–C(6′)); 2.434 (*dd*, *J* = 17.0, 5.6, H_{eq}–C(4)); 5.043 (*m*, H–C(3)); 5.293 (*m*, H–C(3′)); 5.484 (*s*,

H–C(4′)); 5.453 (*dd*, *J* = 15.4, 9.6, H–C(7′)). ^{13}C-NMR (150 MHz, $CDCl_3$): 12.74 (Me(19)); 12.80 (Me(20,20′)); 13.10 (Me(19′)); 21.48 (Me(18)); 23.01 (Me(18′)); 26.33 (Me(17′)); 27.15, 27.20 (*Me*$_3$C); 28.48 (Me(17)); 28.92 (Me(16′)); 30.08 (Me(16)); 36.69 (C(1)); 38.68 (C(2′)); 38.35 (C(4)); 38.62, 38.68 (Me$_3$*C*); 33.01 (C(1′)); 43.96 (C(2)); 55.01 (C(6′)); 68.01 (C(3)); 68.17 (C(3′)); 119.80 (C(4′)); 124.90 (C(11′)); 124.97 (C(11)); 125.36 (C(7)); 125.71 (C(5)); 128.50 (C(7′)); 130.05 (C(15′)); 130.08 (C(15)); 130.92 (C(10′)); 131.40 (C(10)); 132.60 (C(14,14′)); 135.07 (C(9′)); 135.59 (C(9)); 136.46 (C(13)); 136.61 (C(12′)); 137.36 (C(8′)); 137.41 (C(13′)); 137.61 (C(12)); 138.60 (C(8)); 140.27 (C(5′)); 178.23, 178.30 (C=O).

7. *Lutein-3,3′-diyl Bis[(–)-4,7,7-trimethyl-3-oxo-2-oxabicylo[2.2.1]heptane-1-carboxylate]* (**1g**). In the same equipment as in *Exper. 2*, a soln. of 258 mg of **1a** in 10 ml of THF, 5 ml of pyridine, 5 ml of benzene, and a few crystals of 4-(dimethylamino)pyridine was treated at 50° with 390 mg (+)-camphanoyl chloride [12], added in five portions. Then, the solvents were removed *in vacuo*, and the solid residue was taken up in ligroin/AcOEt 9 : 1 and purified on a column of silica gel as described before. The substance isolated from the red main zone was crystalline. Recrystallization from benzene/MeOH gave 316 mg (74.5%) of **1g**. Deep red crystals with a metallic luster. M.p. (*in vacuo*) 225°. UV/VIS (CH_2Cl_2): 270.7 (4.39), 430.8 (4.96), 454.7 (5.13), 484.1 (5.08). CD (CH_2Cl_2): 243.6 (7.94), 286.2 (– 3.00), 338.2 (0.40), 360.8 (– 0.34), 456.4 (with fine structure, 3.85).

8. *Lutein-3,3′-diyl Bis[methyl carbonate]* (**1h**). In the same equipment as in *Exper. 2*, a soln. of 200 mg of **1a** in 20 ml of CH_2Cl_2, 1.8 ml of pyridine and a few crystals of 4-(dimethylamino)pyridine was chilled to 0°, followed by addition of 200 µl of ClCOOMe. Then, the soln. was allowed to reach r.t. and was further stirred for 15 h. The solvents were removed *in vacuo*, the residue was taken up in Et_2O, washed thoroughly with aq. H_2SO_4, H_2O, and brine, dried (Na_2SO_4), filtered, and evaporated: 220 mg of a red crystalline solid. Chromatography on a silica-gel column with ligroin/AcOEt 9 : 1 as described before gave 195 mg of **1h** (m.p. 143–144° (*in vacuo*), which crystallized from THF/MeCN. An anal. sample was prepared by column chromatography on MgO/*Celite* 3 : 1 with benzene/AcOEt 3 : 1 and recrystallized from hot (i-Pr)$_2$O. M.p. (*in vacuo*) 145–146°. UV/VIS (CH_2Cl_2): 272.0 (4.36), 430.6 (4.90), 454.5 (5.06), 484.0 (5.02). CD (CH_2Cl_2): 244.8 (6.75), 288.5 (– 1.13). IR (KBr): 3026, 2956, 2859, 1744, 1441, 1268, 966. ^{1}H-NMR (600 MHz, $CDCl_3$): 0.890 (*s*, Me(17′)); 1.025 (*s*, Me(16′)); 1.092 (*s*, Me(16)); 1.124 (*s*, Me(17)); 1.551 (*dd*, *J* = 14.0, 5.1, H_{ax}–C(2′)); 1.637 (*t*, *J* = 12, H_{ax}–C(2)); 1.666 (*s*, Me(18′)); 1.740 (*s*, Me(18)); *ca.* 1.9 (*m*, H_{eq}–C(2), H_{eq}–C(2′)); 1.913 (*s*, Me(19′)); 1.974 (*s*, Me(19,20)); 1.982 (*s*, Me(20′)); 2.207 (*dd*, *J* = 16.6, 9.5, H_{ax}–C(4)); 2.410 (*d*, *J* = 9.5, H–C(6′)); 2.506 (*dd*, *J* = 16.8, 5.6, H_{eq}–C(4)); 3.784 (*s*, MeO–C(3′)); 3.794 (*s*, MeO–C(3)); *ca.* 4.93 (*m*, H–C(3)); 5.196 (*s*-like, H–C(3′)); 5.437 (*dd*, *J* = 11.6, 9.7, H–C(7′)); 5.575 (*s*, H–C(4′)); *ca.* 6.17 (*m*, H–C(7,8,8′,10,10′)); 6.265 (*d*, *J* = 8.8, H–C(14,14′)); 6.371 (*dd*, *J* = 14.0, 5.4, H–C(12,12′)); 6.63 (*m*, H–C(11,11′,15,15′)). ^{13}C-NMR (150 MHz, $CDCl_3$): 12.80 (Me(19,20,20′)); 13.09 (Me(19′)); 21.47 (Me(18)); 22.94 (Me(18′)); 25.53 (Me(17′)); 28.48 (Me(17)); 28.86 (Me(16′)); 29.98 (Me(16)); 33.28 (C(1′)); 36.84 (C(1)); 39.16 (C(2′)); 38.29 (C(4)); 43.94 (C(2)); 54.89 (C(6′)); 72.50 (C(3)); 72.86 (C(3′)); 119.27 (C(4′)); 124.75 (C(11)); 124.88 (C(11′)); 125.11 (C(5)); 128.09 (C(7′)); 130.07 (C(15′)); 130.11 (C(15)); 131.05 (C(10′)); 131.51 (C(10)); 132.64 (C(14,14′)); 134.94 (C(9′)); 135.52 (C(9)); 136.41 (C(12,12′)); 136.47 (C(13,13′)); 137.69 (C(8′,12′)); 137.94 (C(6)); 138.78 (C(8,8′)); 141.17 (C(5′)).

9. *Lutein-3,3′-diyl Bis[(–)-(1*R*)-2-methyl-5-(1-methylethyl)cyclohexyl carbonate]* (**1i**). In the same equipment as in *Exper. 2*, a soln. of 800 mg of **1a** in 100 ml of THF and 15 ml of pyridine was treated at 60–65° at intervals of 15 min with five portions of 100 µl of (–)-(1*R*)-menthyl chloroformate [13]. After chilling and evaporation of the solvents *in vacuo*, the red crystalline residue was taken up with Et_2O and washed thoroughly with H_2O and brine. After drying (Na_2SO_4) and evaporation of solvents, the residue was dissolved in ligroin (80–95°)/AcOEt 9 : 1 with the help of a few ml of CH_2Cl_2 and applied to a well-settled column of silica gel (as described before). A deep orange-red zone eluted as one of the earliest fractions. After evaporation, a crystalline red compound remained. Yield after recrystallization from CH_2Cl_2/MeCN and THF/MeCN, and drying at 55°/0.92 Torr for 12 h: 984 mg (75%) of **1i**. (The crystals retain solvent molecules, which can be removed by drying *in vacuo* as mentioned.) M.p. (*in vacuo*) 183–183.5°. UV/VIS (CH_2Cl_2): 271.9 (4.38), 431.4 (4.96), 455.0 (5.13), 484.2 (5.08). CD (CH_2Cl_2): 246.0 (7.60), 286.0 (– 3.78), 339.0 (1.74). IR (KBr, only very strong bands): 2955, 2924, 2869, 1734, 1260, 962. ^{1}H-NMR (500 MHz, C_6D_6; only identified signals of the carotenoid core): 0.821 (*s*, Me(17′)); 1.070 (*s*, Me(16,16′)); *ca.* 1.2 (*m*, H_{ax}–C(2′)); 1.135 (*s*, Me(17)); *ca.* 1.45 (*m*, H_{eq}–C(2′)); 1.594 (*s*, Me(18′)); 1.657 (*s*, Me(18)); 1.746 (*t*, *J* = 11.9 H_{ax}–C(2)); 1.876 (*s*, Me(19,20,20′)); 1.793 (*s*, (Me(19′)); 2.011 (*d* with fine structure, *J* = 10.5, H_{eq}–C(2)); *ca.* 2.05 (*m*, H–C(6′), H_{ax}–C(4), H_{eq}–C(2′)); 2.531 (*dd*, *J* = 17.0, 2.5, H_{eq}–C(4)); 5.24 (*m*, H–C(3)); 5.388 (*dd*, *J* = 15.5, 9.7, H–C(7′)); 5.50 (*m*, H–C(4′)); 5.833 (*m*, H–C(3′)); 6.135 (*d*, *J* = 15.5, partial *AB* of H–C(8,7)); 6.2–6.4 (*m*, H–C(8,10,10′,14,14); 6.50 (*dd*-like, H–C(12,12′)); 6.65–6.8 (*m*, H–C(11,11′,15,15′)). ^{13}C-NMR (150 MHz, C_6H_6): 13.13 (Me(19)*); 13.25 (Me(20,20′)*); 13.47 (Me(19′)); 21.92 (Me(18)); 23.39 (Me(18′)); 25.97 (Me(17′)); 29.02 (Me(17)); 29.50

(Me(16′)); 30.46 (Me(16)); 33.83 (C(1′)); 37.31 (C(1)); 39.14 (C(4)); 41.71 (C(2′)); 44.84 (C(2)); 55.58 (C(6′)); 72.27 (C(3)); 72.69 (C(3′)); 121.02 (C(4′)); 125.66 (C(9′,11′)); 125.77 (C(11,9)); 125.97 (C(7)); 126.22 (C(5,7′)); 131.06 (C(15)); 131.13 (C(15′,11)); 132.21 (C(10′)); 132.69 (C(10)); 133.76 (C(12,14′)); 136.05 (C(13)*); 137.01 (C(13′)*); 138.68 (C(8′)); 138.76 (C(14)); 139.68 (C(6,8)); 140.97 (C(5′)). ESI-MS: 955.7 ($[M+Na]^{+\bullet}$). Anal. calc. for $C_{62}H_{92}O_6$ (933.40): C 79.78, H 9.93; found: C 79.90/79.85, H 10.02/10.16.

10. *Zeaxanthin-3,3′-diyl Bis[(−)-(1R)-2-methyl-5-(1-methylethyl)cyclohexyl carbonate]* (**2b**). In the same equipment as in *Exper. 2*, a few crystals of 4-(dimethylamino)pyridine and a few drops of $EtN(i\text{-}Pr)_2$ were added to a soln. of 220 mg (3*R*,3′*R*)-zeaxanthin (**2a**) in 45 ml of boiling CH_2Cl_2, followed by 400 µl of (−)-(1*R*)-menthyl chloroformate in small drops. Heating at reflux was continued for 2 h. Workup as in *Exper. 9*, and column chromatography on silica gel with ligroin/AcOEt 9 :1 yielded a viscous deep red oil, which on uptake in hot THF and addition of a double volume of MeCN spontaneously crystallized as deep-orange-red crystals: 211 mg (58%) of **2b**. M.p. (*in vacuo*) 206°. UV/VIS (CH_2Cl_2): 279.8 (4.32), 437 (sh, 4.91), 460.42 (5.05), 488.64 (4.98). CD (CH_2Cl_2): 249.5 (7.43), 287.9 (−12.17), 346.4 (2.38)). IR (KBr): 2956, 2926, 2870, 1737, 1263, 962. ^{1}H-NMR (500 MHz, C_6H_6): 1.071 (Me(16,16′)); 1.135 (Me(17,17′)); 1.657 (Me(18,18′)); 1.746 (*t*, $J=11.9$, H_{ax}−C(2,2′)); 1.876 (Me (19,19′,20,20′)); 2.011 (*d*, with fine structure, $J=10.5$, H_{eq}−C(2,2′)); *ca.* 2.25 (*m*, H−C(6,6′), H_{ax}−C(4,4′)); 2.531 (*dd*, $J=17.0$, 5.5, H_{eq}−C(4,4′)); 5.239 (*m*, H−C(3,3′)); 6.135 (part of *AB* of C(7,8,7′,8′)); *ca.* 6.63 (*m*, H−C(8,8,10,10′,14,14′)); 6.501 (*d*-like, $J=14.9$, 3.7, H−C(12,12′)); *ca.* 6.75 (*m*, H−C(11,11′,15,15′)). ^{13}C-NMR (C_6H_6, 125 MHz): 13.12 (Me(19,19′)); 13.25 (Me(20,20′)); 21.92 (Me(18,18′)); 29.02 (Me(17,17′)*); 30.57 (Me(16,16′)*); 37.30 (C(1,1′)); 39.14 (C(4,4′)); 44.85 (C(2,2′)); 72.28 (C(3,3′)); 125.75 (C(11,11′)); 125.96 (C(7,7′)); 126.22 (C(5,5′)); 131.11 (C(15,15′)); 132.70 (C(10,10′)); 133.78 (C(14,14′)); 136.03 (C(13,13′)*); 137.09 (C(9,9′)*); 138.55 (C(6,6′)); 138.69 (C(12,12′)); 139.68 (C(8,8′)); 155.74 (C=O). Anal. calc. for $C_{62}H_{92}O_6$ (933.40): C 79.78, H 9.93; found: C 79.70/79.60, H 9.91/9.84.

11. *X-Ray Crystal-Structure Determinations for Compounds* **1i** *and* **2b** (*Table 4* and *Fig. 1*)[2]). All measurements were conducted on a *Nonius KappaCCD* area-detector diffractometer [32] with graphite-monochromated MoK_α radiation (λ 0.71073 Å) and an *Oxford Cryosystems Cryostream 700* cooler. The data collection and refinement parameters are given in *Table 4*, while views of the molecules are shown in *Fig. 1*. Data reduction was performed with HKL DENZO and SCALEPACK [33]. The intensities were corrected for *Lorentz* and polarization effects, but not for absorption, while equivalent reflections were merged. The structures were solved by direct methods with SHELXS97 [34] for **1i** and SIR92 [35] for **2b**. In each case, the enantiomer defined in the model was chosen to correspond with the known (1*R*)-menthyl carbonate moieties in the molecules.

For **1i**, the menthyl group at one end of the molecule is disordered over two conformations. Two positions were defined for all atoms of this group, and the site occupation factor of the major conformation was refined to 0.63(2). Similarity restraints were applied to the chemically equivalent bond lengths and angles within the disordered region. Neighbouring atoms within and between each conformation of the disordered group were also restrained to have similar atomic-displacement parameters.

The non-H-atoms of each structure were refined anisotropically. All of the H-atoms were placed in geometrically calculated positions and refined with a riding model where each H-atom was assigned a fixed isotropic displacement parameter with a value equal to $1.2U_{eq}$ of its parent atom ($1.5U_{eq}$ for the Me groups). The structures were refined on F^2 using full-matrix least-squares procedures, which minimized the function $\Sigma w(F_o^2 - F_c^2)^2$). Corrections for secondary extinction were applied. For **2b**, two low angle reflections were omitted from the final refinement of each structure, because the observed intensities of these reflections were much lower than the calculated values as a result of being partially obscured by the beam stop. Neutral-atom-scattering factors for non-H-atoms were taken from [36a], and the scattering factors for H-atoms were taken from [37]. Anomalous dispersion effects were included in F_c [38]; the values for f' and f'' were those of [36b]. The values of the mass attenuation coefficients were those of [36c]. All calculations were performed using SHELXL97 [39]. The crystallographic diagrams were drawn using ORTEPII [40] and PLATON [41].

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[2]) CCDC-221221 and -221222 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge *via* www.ccdc.cam.ac.uk/conts/retrieving.html or from the *Cambridge Crystallographic Data Centre*, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

Table 4. *Crystallographic Data for Compounds* **1i** *and* **2b**

	1i	**2b**
Crystallized from	CH_2Cl_2 / methylcyclohexane	THF / MeCN
Empirical formula	$C_{62}H_{92}O_6$	$C_{62}H_{92}O_6$
Formula weight [g·mol^{-1}]	933.40	933.40
Crystal color, habit	orange, plate	orange, needle
Crystal dimensions [mm]	$0.05 \times 0.15 \times 0.18$	$0.02 \times 0.07 \times 0.25$
Temp. [K]	160(1)	160(1)
Crystal system	triclinic	triclinic
Space group	*P*1	*P*1
Z	1	1
Reflections for cell determination	4760	5036
2θ Range for cell determination [°]	4–50	4–50
Unit-cell parameters *a* [Å]	7.4958(1)	8.2021(3)
b [Å]	7.7843(2)	11.5998(5)
c [Å]	24.8411(5)	16.1682(9)
α [°]	92.7700(7)	81.577(2)
β [°]	93.5415(6)	85.896(2)
γ [°]	99.533(1)	72.405(3)
V [Å^3]	1424.20(5)	1449.9(1)
F(000)	512	512
D_x [g·cm^{-3}]	1.088	1.069
μ(MoK_α) [mm^{-1}]	0.0677	0.0665
Scan type	ϕ and ω	ϕ and ω
$2\theta_{(max)}$ [°]	50	50
Total reflections measured	22185	23340
Symmetry-independent reflections	5003	5075
R_{int}	0.054	0.097
Reflections with $I > 2\sigma(I)$	3565	3144
Reflections used in refinement	5003	5073
Parameters refined; restraints	724; 270	630; 3
$R(F)$ ($I > 2\sigma(I)$ reflections)	0.0467	0.0550
$wR(F^2)$ (all reflections)	0.1176	0.1401
Weighting parameter [*a*][a])	0.0682	0.0611
Goodness-of-fit	1.013	0.998
Secondary extinction coefficient	0.024(3)	0.008(2)
Final Δ_{max}/σ	0.001	0.001
$\Delta\rho$ (max; min) [e Å^{-3}]	0.16; −0.16	0.26; −0.18

[a]) $w^{-1} = \sigma^2(F_o^2) + (aP)^2$ where $P = (F_o^2 + 2F_c^2)/3$.

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