Pergamon

Tetrahedron 55 (1999) 1063–1078

TETRAHEDRON

Reverse Asymmetric Catalytic Epoxidation of Unfunctionalized Alkenes

Andreas Scheurer and Paul Mosset*

Laboratoire de Synthèses et Activations de Biomolécules, associé au CNRS

Ecole Nationale Supérieure de Chimie de Rennes, Avenue du Général Leclerc, F-35700 Rennes, France

Martina Spiegel and Rolf W. Saalfrank*

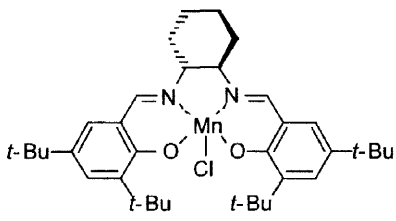
Institut für Organische Chemie der Universität Erlangen-Nürnberg

Henkestraße 42, D-91054 Erlangen, Germany

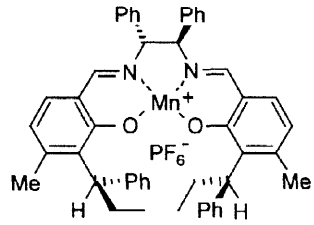
Received 30 September 1998; accepted 24 November 1998

Abstract: New salen Mn(III) complexes (*S,S*)-**6a-e** prepared from tartaric-derived alicyclic C_2 symmetric vicinal diamines were studied in the catalysis of the asymmetric epoxidation of unfunctionalized alkenes. Although the enantioselectivities obtained were not as high as for Jacobsen and Katsuki catalysts, the most striking result was the reversed asymmetric induction.

The asymmetric epoxidation of alkenes is extensively studied in organic chemistry, since optically active epoxides are useful intermediates for the synthesis of many natural products. In recent years, chiral salen Mn(III) complexes have proven to be potent catalysts for the enantioselective epoxidation of unfunctionalized alkenes. In particular, Jacobsen[1a,b] and Katsuki[1c-e] synthesized (*R,R*)-**1** and (*R,R*)-**2**, starting from 1,2-cyclohexanediamine or 1,2-diphenylethylenediamine and salicylaldehydes substituted with bulky groups.



(*R,R*)-**1**



(*R,R*)-**2**

Other salen ligands have been prepared with various diamine and aromatic units,[1b,2] however, the potential of the corresponding salen Mn(III) complexes for the enantioselective epoxidation of unfunctionalized alkenes was not reported. Starting from L-tartaric acid, we recently synthesized a series of enantiomerically pure, alicyclic vicinal diamines with terminal oxygen functionalities, e.g., (2*S*,3*S*)-**3a-e**.[3]

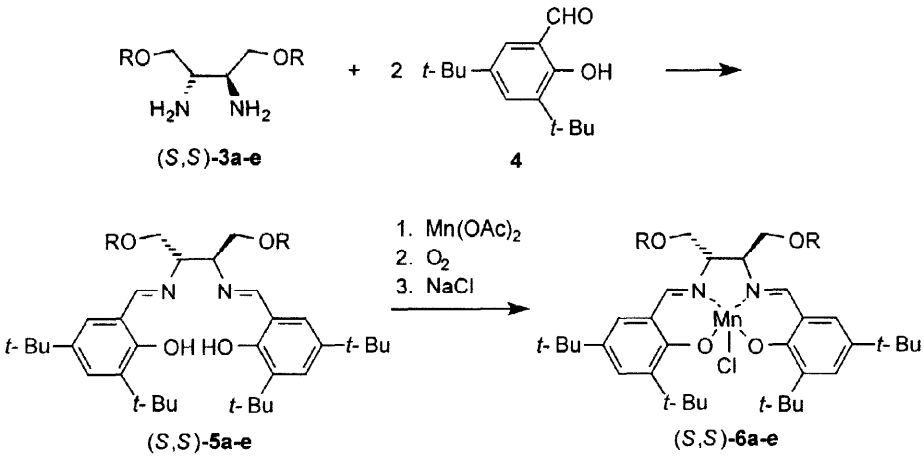
0040-4020/99/$ - see front matter
PII: S0040-4020(98)01106-5

In this article, we wish to report on the enantioselective epoxidation of unfunctionalized *Z*-alkenes using the new salen Mn(III) catalysts (*S,S*)-**6a-e** prepared from the diamines (*S,S*)-**3a-e**. The inversion of the stereochemistry of the epoxides induced by using catalyst (*S,S*)-**6a-e**, is highlighted and compared to the results obtained with (*R,R*)-**1** and (*R,R*)-**2**. In order to compare the enantioselectivity data with that observed for the Jacobsen catalyst **1**, the readily available starting material 3,5-di-*tert*-butylsalicylaldehyde **4** was used for the preparation of the salen complexes (*S,S*)-**6a-e**.

RESULTS AND DISCUSSIONS

Preparation of the Salen Mn(III) Complexes (*S,S*)-6a-e

Following literature procedures,[4] the reaction of C_2 symmetric vicinal diamines (*S,S*)-**3a-e** with 3,5-di-*tert*-butylsalicylaldehyde **4** in ethanol at 80 °C yielded the salen derivatives (*S,S*)-**5a-e**. Complexation of manganese(II) acetate by (*S,S*)-**5** readily afforded a Mn(II) intermediate, which was oxidized by simple bubbling of air. Anion exchange was accomplished by the addition of brine to yield complexes (*S,S*)-**6a-e**.



3, 5, 6	a	b	c	d	e
R	H	Me	Bn	2-NaphCH$_2$	Tr

Scheme 1 : Preparation of C_2 symmetric salen ligands (*S,S*)-**5a-e** and their Mn(III) complexes (*S,S*)-**6a-e**.

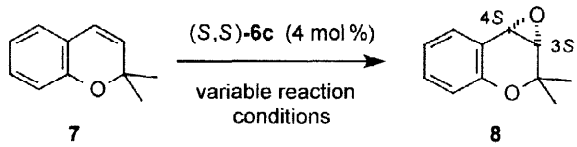
Catalytic Enantioselective Epoxidation of Unfunctionalized Alkenes

1. Dependence of Terminal Oxidants in the Enantioselective Epoxidation of 2,2-Dimethylchromene 7 Catalyzed by (S,S)-6c

The first parameter studied to control the enantioselectivity of the epoxidation was the terminal oxidant. For that purpose 2,2-dimethylchromene **7** and salen Mn(III) catalyst (*S,S*)-**6c** (4 mol%) were chosen as the

model system. It turned out that both the enantioselectivity and the yield varied widely with the reaction conditions used (Table 1). The highest yield for **8** (88%, 54% ee, entry 2) was observed when using aqueous sodium hypochlorite (bleach) at 0 °C in the presence of 4-phenylpyridine *N*-oxide (4-PPNO).[5] Combination of *m*-chloroperbenzoic acid (MCPBA) and *N*-methylmorpholine *N*-oxide monohydrate (NMO·H_2O) at –78 °C[6] (entry 4) produced the highest ee together with good yield for **8**. In contrast, no enantioselectivity was observed when the same reaction was run at higher temperature (0 °C, entry 3), indicating that the reaction temperature has strong control on the enantioselectivity of the epoxidation. Other variations in the reaction conditions ($NaIO_4$/Bu_4NBr/imidazole[7], PhIO[8], O_2/^{t}BuCHO[8,9]) all proved to be less efficient (Table 1). It is noteworthy that in all cases studied, the major enantiomer of epoxide **8** had the (3*S*,4*S*)-configuration, which is in agreement with a common Mn(V)-oxo intermediate.

Table 1. Epoxidation of 2,2-dimethylchromene **7** catalyzed by salen Mn(III) complex (*S*,*S*)-**6c**.



7 **8**

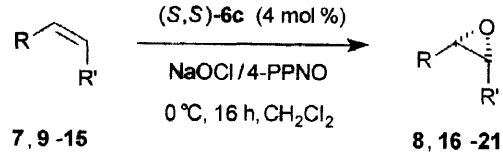
Entry	Oxidant	Additive[a]	Equiv. Oxi.	Solvent	Temp. (°C)	Time (h)	Yield (%)	% ee[b] (Config.)
1	NaOCl	-	2	CH_2Cl_2	0	16	78	55 (*3S,4S*)
2	NaOCl	4-PPNO	2	CH_2Cl_2	0	16	88	54 (*3S,4S*)
3	MCPBA	NMO·H_2O	2	CH_2Cl_2	0	1.5	63	3 (*3S,4S*)
4	MCPBA	NMO·H_2O	2	CH_2Cl_2	-78	1.5	76	69 (*3S,4S*)
5	MCPBA	NMO	2	CH_2Cl_2	-78	1.5	68	65 (*3S,4S*)
6	$NaIO_4$/Bu_4NBr	Imidazole	2.5	CH_2Cl_2	RT	9	38	37 (*3S,4S*)
7	$NaIO_4$/Bu_4NBr	Imidazole	2.5	CH_2Cl_2	0	18	14	46 (*3S,4S*)
8	PhIO	NMI	2	CH_3CN	RT	8	41	13 (*3S,4S*)
9	O_2/^{t}BuCHO	NMI	excess	C_6H_5F	RT	18	3	29 (*3S,4S*)

a) 4-PPNO: 4-phenylpyridine *N*-oxide; NMO: anhydrous *N*-methylmorpholine *N*-oxide; NMI: *N*-methylimidazole.
b) The determination of % ee was carried out by ^{1}H NMR analysis in $CDCl_3$ using Eu(hfc)$_3$.
The configuration was assigned by polarimetry according to ref. [10].

2. *Enantioselective Epoxidation of a Representative Selection of Unfunctionalized Olefins with NaOCl/4-PPNO and MCPBA/NMO in the Presence of Catalyst (S,S)-6c*

As summarized in Table 2, eight unfunctionalized olefins were epoxidized with aqueous sodium hypochlorite/4-PPNO at 0 °C in the presence of catalyst (*S*,*S*)-**6c**. The highest asymmetric inductions were obtained for 2,2-dimethylchromene **7** (entry 1, 54% ee), 6-methoxy-2,2-dimethylchromene **12** (entry 5, 62% ee) and indene **15** (entry 8, 55% ee). Unsatisfactory results (decrease in yield and % ee) were obtained for chromene derivatives substituted with an electron-withdrawing group in the 6-position (entries 2 and 3).

Table 2. Epoxidation of unfunctionalized olefins catalyzed by complex (*S,S*)-**6c** using aqueous sodium hypochlorite/4-PPNO as the terminal oxidant at 0 °C.



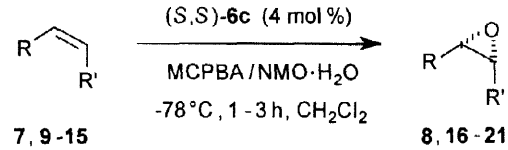
7, 9 -15 **8, 16 -21**

Entry	Olefin	Yield (%)	% ee[a] (Config.)
1	2,2-Dimethylchromene **7**	88	54 (*3S,4S*)[b]
2	6-Cyano-2,2-dimethylchromene **9**	73	36 (*3S,4S*)[b]
3	6-Nitro-2,2-dimethylchromene **10**	60	41 (*3S,4S*)[c]
4	6-Chloro-2,2-dimethylchromene **11**	67	53 (*3S,4S*)[c]
5	6-Methoxy-2,2-dimethylchromene **12**	78	62 (*3S,4S*)[c]
6	7-Methoxy-2,2-dimethylchromene **13**	decomposition	
7	1,2-Dihydronaphthalene **14**	77	48 (*1S,2R*)[b]
8	Indene **15**	92	55 (*1S,2R*)[d]

a) The determination of % ee was carried out by ^{1}H NMR analysis in $CDCl_3$ using $Eu(hfc)_3$.
b) Assigned by polarimetry according to ref. [11].
c) The absolute configuration was assigned by shift reagent studies by analogy to entries 1 and 2.
d) Configuration was proved by ^{1}H NMR analysis in $CDCl_3$ using $Eu(hfc)_3$ to be opposite of that of a standard (1*R*,2*S*)-epoxide prepared using (*R,R*)-**1**.

Epoxidation with MCPBA/NMO•H_2O at –78 °C in the presence of catalyst (*S,S*)-**6c** in all cases afforded somewhat lower yields but, generally, higher enantioselectivities (Table 3).

Table 3. Epoxidation of unfunctionalized olefins catalyzed by complex (*S,S*)-**6c**, using MCPBA/NMO•H_2O as the terminal oxidant at -78°C.

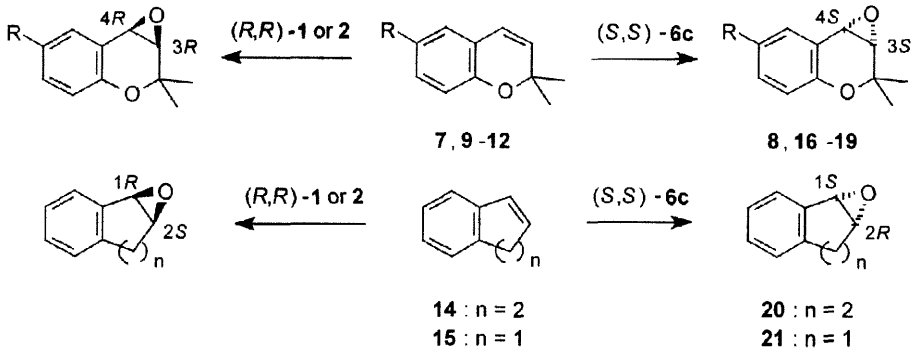


7, 9 -15 **8, 16 - 21**

Entry	Olefin	Time (h)	Yield[a] (%)	% ee[b] (Config.)
1	2,2-Dimethylchromene **7**	1.5	76	69 (*3S,4S*)
2	6-Cyano-2,2-dimethylchromene **9**	3	56	50 (*3S,4S*)[c]
3	6-Nitro-2,2-dimethylchromene **10**	3	49	52 (*3S,4S*)
4	6-Chloro-2,2-dimethylchromene **11**	1	59	48 (*3S,4S*)
5	6-Methoxy-2,2-dimethylchromene **12**	3	59	64 (*3S,4S*)
6	7-Methoxy-2,2-dimethylchromene **13**	3	decomposition	
7	1,2-Dihydronaphthalene **14**	1	72	50 (*1S,2R*)
8	Indene **15**	1	78	43 (*1S,2R*)

a) 5-10% starting material was recovered.
b) Assignment according to captions given in Table 2.
c) Configuration was verified by chiral HPLC to be opposite of that of a standard epoxide prepared using (*R,R*)-**1**.

Regardless of the reaction conditions used, all major enantiomers of the epoxides **8**, **16-21** investigated showed equivalent stereochemistry (Scheme 2). Contrary to the Jacobsen catalyst (*R,R*)-**1** and the Katsuki catalyst (*R,R*)-**2**, stereochemically identical (*S,S*)-**6c**[12] afforded the opposite enantiomers of the epoxides.[1,4,13-16] This unexpected reversal of enantioselectivity is likely due to the presence of the oxygen functionality[17] in the diimine moiety. Although, an alternative approach of the alkene to the intermediate Mn(V)-oxo species could be favoured, presently no final explanation for this result can be given.[18]

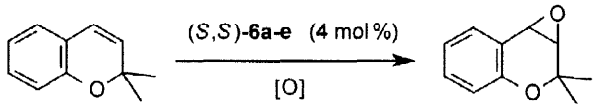


Scheme 2 : Stereochemistry of the major enantiomers of the epoxides **8**, **16-21** (R = H, CN, NO_2, Cl, OMe) using (*R,R*)-**1**, (*R,R*)-**2**, and (*S,S*)-**6c**.

3. *Influence of the Oxygen Functionality in Catalysts (S,S)-6a-e on the Enantioselective Epoxidation of 2,2-Dimethylchromene 7*

The influence of the different oxygen functionalities of catalysts (*S,S*)-**6a-e** on the enantioselective epoxidation of 2,2-dimethylchromene **7** was studied with both NaOCl/4-PPNO[19] and MCPBA/NMO•H_2O as terminal oxidants (Table 4).

Table 4. Epoxidation of 2,2-dimethylchromene **7** catalyzed by salen Mn(III) complexes (*S,S*)-**6a-e**, using MCPBA/NMO•H_2O or aqueous sodium hypochlorite as terminal oxidants.



7 **8**

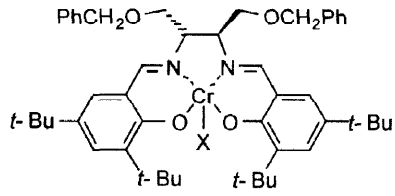
			MCPBA[a,b]		NaOCl[a,c]	
Entry	Catalyst	R	Yield (%)	% ee (Config.)	Yield[d] (%)	% ee [d] (Config.)
1	(*S,S*)-**6a**	H	67	48 (3*S*,4*S*)	66 [16]	41 [49] (3*S*,4*S*)
2	(*S,S*)-**6b**	Me	45	60 (3*S*,4*S*)	64 [20]	64 [65] (3*S*,4*S*)
3	(*S,S*)-**6c**	Bn	76	69 (3*S*,4*S*)	88	54 (3*S*,4*S*)
4	(*S,S*)-**6d**	2-NaphCH_2	69	57 (3*S*,4*S*)	58 [14]	60 [58] (3*S*,4*S*)
5	(*S,S*)-**6e**	Tr	15	10 (3*R*,4*R*)	71 [9]	58 [53] (3*S*,4*S*)

a) All reactions were carried out in presence of 2 equivalents of oxidant.
b) MCPBA/NMO•H_2O, CH_2Cl_2, 1 h, -78 °C.
c) NaOCl/4-PPNO, CH_2Cl_2, 16 h, 0 °C.
d) Figures in brackets: Yield and ee of side product (3*S*,4*S*)-6-chloro-3,4-epoxy-2,2-dimethylchromane[19] arising from chlorination of the aromatic ring.

It was shown that the enantioselectivities were comparable in all cases when the hydroxyl group of the salen Mn(III) catalyst was protected. The only exception was found for catalyst (*S,S*)-**6e** with O-trityl substituents using MCPBA. In this case the enantioselectivities and the yields of **8** were low. Furthermore, (*S,S*)-**6e** afforded the same enantioselectivities as (*R,R*)-**1** and (*R,R*)-**2**. Catalyst (*S,S*)-**6a**, with free hydroxyl groups, formed epoxides with noticeably lower ee compared to (*S,S*)-**6b-d**, but with the same enantioselectivities.

4. Investigation of Salen Cr(III) Catalysts (S,S)-22a,b in the Enantioselective Epoxidation of 2,2-Dimethylchromene 7

Salen Cr(III) catalysts are known to give opposite enantioselectivities with respect to their Mn(III) analogs for the epoxidation of *Z*-alkenes.[20] Consequently, we investigated the function of the salen Cr(III) catalysts (*S,S*)-**22a,b** with O-benzyl groups. The compounds (*S,S*)-**22a,b** were obtained by complexation of $CrCl_2$ with diimine (*S,S*)-**5c** followed by oxygen oxidation and counterion exchange with the corresponding silver salt.[21]



(*S,S*)-22

a: X = PF_6
b: X = OTf

It turned out that only (*S,S*)-**22a** was an active catalyst for the enantioselective epoxidation of 2,2-dimethylchromene **7** using iodosylbenzene as terminal oxidant and triphenylphosphine oxide as additive (Table 5, entry 3). Thus 3,4-epoxy-2,2-dimethylchromane **8** was rapidly formed in good yield with 33% ee. It is noteworthy that (*S,S*)-**22a** leads to higher enantioselectivities than catalyst (*S,S*)-**6c** using the same terminal oxidant (entry 1, 13% ee). For both catalysts (*S,S*)-**6c** and (*S,S*)-**22a** the major enantiomer was (3*S*,4*S*)-**8** whereas Gilheany and Bousquet obtained opposite enantioselectivities in the epoxidation of *Z*-olefins using an analogous Cr(III) catalyst to (*R,R*)-**1**.[20]

Table 5. Epoxidation of 2,2-dimethylchromene **7** in the presence of salen Mn(III) complex (*S,S*)-**6c** and salen Cr(III) complexes (*S,S*)-**22a,b**.

Entry	Catalyst	Oxidant[a]	Additive	Solvent	Temp. (°C)	Time (h)	Yield (%)	% ee (Config.)
1	(*S,S*)-**6c**	PhIO	NMI	CH_3CN	RT	8	41	13 (3*S*,4*S*)
2	(*S,S*)-**6c**	MCPBA	NMO•H_2O	CH_2Cl_2	-78	1.5	76	69 (3*S*,4*S*)
3	(*S,S*)-**22a**	PhIO	$OPPh_3$	CH_3CN	0	1	71	33 (3*S*,4*S*)
4	(*S,S*)-**22a**	MCPBA	NMO•H_2O	CH_2Cl_2	-78	3	n. r.[b]	-
5	(*S,S*)-**22b**	PhIO	$OPPh_3$	CH_3CN	0	8	n. r.[b]	-
6	(*S,S*)-**22b**	MCPBA	NMO•H_2O	CH_2Cl_2	-78	3	n. r.[b]	-

a) All reactions were carried out in presence of 2 equivalents of oxidant.
b) No reaction.

CONCLUSION

In conclusion, compared with the Jacobsen catalyst (*R,R*)-**1** or the Katsuki catalyst (*R,R*)-**2**, epoxidation of unfunctionalized olefins with aqueous sodium hypochlorite/4-PPNO or MCPBA/NMO•H_2O and salen Mn(III) catalysts (*S,S*)-**6a-e** led to somewhat lower enantioselectivities. But, most remarkably, the major enantiomers of most of the epoxides generated in the presence of (*S,S*)-**6a-e**[12] exhibited opposite absolute configuration compared with the results obtained with (*R,R*)-**1** and (*R,R*)-**2**, indicating an unusual reversal of asymmetric induction. The hydroxyl or ether groups of (*S,S*)-**6a-d** were of only little effect on the degree of enantioselectivity.

EXPERIMENTAL SECTION

Data for the salen ligands

(2S,3S)-N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-dihydroxy-2,3-diaminobutane (S,S)-5a

To a solution of (2*S*,3*S*)-1,4-dihydroxy-2,3-diaminobutane (2*S*,3*S*)-**3a** (54 mg, 0.45 mmol) in distilled water (0.75 mL), was added ethanol (3 mL) and the resulting mixture was heated at reflux. A solution of 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde **4** (211 mg, 0.9 mmol) in ethanol (2 mL) was added continously over 15 min *via* syringe. The syringe was rinsed with ethanol (0.5 mL) and the yellow slurry was stirred at reflux for 2 h. After evaporation of the solvents, the crude solid was redissolved in CH_2Cl_2 (4 mL) and washed with water (2 x 1.5 mL) and brine (1 mL). After drying over $MgSO_4$, the solvent was removed under vacuum, and the crude salen ligand was isolated as a yellow powder. Chromatography on silica gel (gradient elution from CH_2Cl_2 to 2% MeOH/CH_2Cl_2) afforded pure (2*S*,3*S*)-**5a** as a yellow solid (185 mg, 73% yield); M.p. 97-99 °C; R_f = 0.11 with 1% MeOH/CH_2Cl_2; IR (Nujol, NaCl): ν 3295 (broad), 1631, 1597, 1441, 1361, 1273, 1251, 1203, 1174, 1056, 879, 827, 803, 774 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 13.37 (broad s, 2H, OH of phenol), 8.42 (s, 2H, CH=N), 7.37 (d, 2H, *J* = 2.4 Hz, CH of phenol), 7.07 (d, 2H, *J* = 2.4 Hz, CH of phenol), 3.93 (pseudo dd, 2H, *J* = 11.2, 4.0 Hz, OCH_2-CH)[22], 3.86 (pseudo dd, 2H, *J* = 11.2, 6.7 Hz, OCH_2-CH)[22], 3.68-3.61 (m, 2H, CH-N=C)[22], 2.15-1.55 (broad s, 2H, OH of diol), 1.42 (s, 18H, *t*-Bu), 1.27 (s, 18H, *t*-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.52 (2C, CH=N), 158.12 ($2C_{ipso}$ α to OH), 140.23 ($2C_{ipso}$ α to *t*-Bu), 136.80 ($2C_{ipso}$ α to *t*-Bu), 127.48 (2C, CH of phenol), 126.34 (2C, CH of phenol), 117.54 ($2C_{ipso}$ α to imine), 72.10 (2C, CH-N=C), 63.69 (2C, $HOCH_2$-CH), 35.03 (2C, $C(CH_3)_3$), 34.10 (2C, $C(CH_3)_3$), 31.43 (6C, $C(CH_3)_3$), 29.39 (6C, $C(CH_3)_3$); MS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{34}H_{52}N_2O_4$ 552.4 $[M]^+$, found 551 (26), 552 (85), 553 (100), 554 (33), 555 (7); $[\alpha]_D^{24}$ = -81.6, $[\alpha]_{578}^{24}$ = -88.1, $[\alpha]_{546}^{24}$ = -111.9 (c = 1.0, $CHCl_3$); Anal. Calcd for $C_{34}H_{52}N_2O_4$: C, 73.87; H, 9.48; N, 5.07. Found: C, 73.36; H, 9.19; N, 4.96.

(2S,3S)-N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-dimethoxy-2,3-diaminobutane (S,S)-5b

The same procedure as described for (2*S*,3*S*)-**5a** was followed. To a solution of (2*S*,3*S*)-1,4-dimethoxy-2,3-diaminobutane (2*S*,3*S*)-**3b** (30 mg, 0.2 mmol) in distilled water (0.5 mL) and ethanol (1.5 mL) at reflux was added a solution of 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde **4** (94 mg, 0.4 mmol) in ethanol (1 mL plus 0.2 mL for rinsing). Chromatography on silica gel (gradient elution from petroleum ether to 8% *tert*-butyl methyl ether/petroleum ether) afforded the pure salen ligand (2*S*,3*S*)-**5b** as yellow crystals (97 mg, 84% yield); M.p. 58-60 °C; R_f = 0.15 with 5% ethyl acetate/petroleum ether; IR (Nujol, NaCl): ν 1631, 1598, 1443, 1362, 1272, 1251, 1202, 1175, 1021, 952, 773 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 13.57 (broad s, 2H, OH), 8.42 (s, 2H, CH=N), 7.38 (d, 2H, *J* = 2.4 Hz, CH of phenol), 7.10 (d, 2H, *J* = 2.4 Hz, CH of phenol), 3.78-3.71 (m, 2H,

CH-N=C)[22], 3.67 (pseudo dd, 2H, J = 9.5, 4.8 Hz, OCH$_2$-CH)[22], 3.48 (pseudo dd, 2H, J = 9.5, 6.9 Hz, OCH$_2$-CH)[22], 3.34 (s, 6H, OCH$_3$), 1.44 (s, 18H, t-Bu), 1.30 (s, 18H, t-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.68 (2C, CH=N), 158.38 (2C$_{ipso}$ α to OH), 139.82 (2C$_{ipso}$ α to t-Bu), 136.80 (2C$_{ipso}$ α to t-Bu), 127.16 (2C, CH of phenol), 126.16 (2C, CH of phenol), 117.67 (2C$_{ipso}$ α to imine), 73.35 (2C, OCH$_2$-CH), 69.31 (2C, CH-N=C), 59.13 (2C, OCH$_3$), 35.07 (2C, C(CH$_3$)$_3$), 34.10 (2C, C(CH$_3$)$_3$), 31.48 (6C, C(CH$_3$)$_3$), 29.39 (6C, C(CH$_3$)$_3$); MS (FAB, m-nitrobenzylic alcohol matrix) m/z (%): calcd for $C_{36}H_{56}N_2O_4$ 580.4 $[M]^+$, found 579 (33), 580 (100), 581 (95), 582 (32), 583 (8); $[\alpha]_D^{24}$ = +27.3, $[\alpha]_{578}^{24}$ = +28.0, $[\alpha]_{546}^{24}$ = +30.0 (c = 1.0, $CHCl_3$); Anal. Calcd for $C_{36}H_{56}N_2O_4$: C, 74.44; H, 9.72; N, 4.82. Found: C, 74.65; H, 9.54; N, 4.61.

(2S,3S)-N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(phenylmethoxy)-2,3-diaminobutane (S,S)-5c

To a solution of (2*S*,3*S*)-1,4-bis(phenylmethoxy)-2,3-diaminobutane (*S*,*S*)-**3c** (640 mg, 2.1 mmol) in distilled water (3 mL) was added ethanol (13 mL) and the resulting mixture was heated at reflux. A solution of 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde **4** (980 mg, 4.2 mmol) in ethanol (8 mL) was added continously over 30 min. Transfer of the aldehyde was completed by rinsing with ethanol (2 mL), and the yellow slurry was stirred at reflux for 2 h before heating was discontinued. Water (4.8 mL) was added and the stirred mixture was cooled to 5 °C over 2 h and maintained at that temperature for 1 additional hour. The product was collected by vacuum filtration and washed with some cold ethanol. The crude solid was redissolved in CH_2Cl_2 (10 mL) and washed with water (2 x 6 mL) and brine (2 mL). After drying over $MgSO_4$, the solvent was removed under vacuum, and the salen ligand (*S*,*S*)-**5c** was isolated as a yellow powder (1.32 g, 86% yield); M.p. 72°C; R_f = 0.15 with 5% ethyl acetate/petroleum ether; IR (Nujol, NaCl): ν 3088, 3064, 3030, 1743, 1630, 1596, 1363, 1272, 1251, 1100, 735, 699 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.59 (s, 2H, OH), 8.39 (s, 2H, CH=N), 7.38 (d, 2H, J = 2.3 Hz, CH of phenol), 7.35-7.22 (m, 10H of benzyl), 7.06 (d, 2H, J = 2.3 Hz, CH of phenol), 4.52 (d, 2H, J = 12.2 Hz, CH$_2$Ph), 4.47 (d, 2H, J = 12.2 Hz, CH$_2$Ph), 3.86-3.80 (m, 2H, CH-N=C)[22], 3.74 (pseudo dd, 2H, J = 9.5, 5.0 Hz, OCH$_2$-CH)[22], 3.56 (pseudo dd, 2H, J = 9.5, 6.5 Hz, OCH$_2$-CH)[22], 1.45 (s, 9H, t-Bu), 1.30 (s, 9H, t-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.84 (2C, CH=N), 158.40 (2C$_{ipso}$ α to OH), 139.78 (2C$_{ipso}$ α to t-Bu), 138.02 (2C$_{ipso}$ α to t-Bu), 136.79 (2C$_{ipso}$ of benzyl), 128.38 (4C$_{meta}$ of benzyl), 127.69 (4C$_{ortho}$ of benzyl), 127.65 (2C$_{para}$ of benzyl), 127.11 (2C, CH of phenol), 126.14 (2C, CH of phenol), 117.70 (2C$_{ipso}$ α to imine), 73.25 (2C, CH$_2$Ph), 70.79 (2C, OCH$_2$-CH), 69.19 (2C, CH-N=C), 35.07 (2C, C(CH$_3$)$_3$), 34.11 (2C, C(CH$_3$)$_3$), 31.49 (6C, C(CH$_3$)$_3$), 29.40 (6C, C(CH$_3$)$_3$); $[\alpha]_D^{23}$ = +24.2, $[\alpha]_{578}^{23}$ = +25.2, $[\alpha]_{546}^{23}$ = +28.2 (c = 5.8, $CHCl_3$); MS (FAB, m-nitrobenzylic alcohol matrix) m/z (%): calcd for $C_{48}H_{64}N_2O_4$ 732.5 $[M]^+$, found 730 (5), 731 (39), 732 (90), 733 (100), 734 (42), 735 (11); Anal. Calcd for $C_{48}H_{64}N_2O_4$: C, 78.65; H, 8.8; N, 3.82. Found: C, 78.98; H, 9.02; N, 3.74.

(2S,3S)-N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis[(2-naphtyl)methoxy]-2,3-diaminobutane (S,S)-5d

The same procedure as described for (2*S*,3*S*)-**5a** was followed with (2*S*,3*S*)-1,4-bis[(2-naphthyl)methoxy]-2,3-diaminobutane (2*S*,3*S*)-**3d** (118 mg, 0.29 mmol), distilled water (0.8 mL), and ethanol (4.5 mL) to which was added at reflux over 10 min a solution of 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde **4** (140 mg, 0.59 mmol) in ethanol (2 mL plus 1 mL for rinsing). Chromatography on silica gel using ethyl acetate/petroleum ether 2:98 as eluent afforded purified (2*S*,3*S*)-**5d** as a yellow solid (209 mg, 87% yield); M.p. 94 °C; R_f= 0.17 with 5% ethyl acetate/petroleum ether; IR (Nujol, NaCl): ν 3054, 1629, 1602, 1441, 1362, 1272, 1251, 1173, 1098, 854, 817, 752 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ 13.62 (broad s, 2H, OH), 8.44 (s, 2H, CH=N), 7.81-7.67 (m, 6H of 2-naph), 7.70 (broad d, J = 1.4 Hz, 2H of 2-naph), 7.47-7.39 (m, 4H of 2-naph), 7.39 (d, 2H, J = 2.4 Hz, CH of phenol), 7.38 (dd, J = 8.3, 1.6 Hz, 2H of 2-naph), 7.06 (d, 2H, J = 2.4 Hz, CH of phenol), 4.67 (d, 2H, J = 12.5 Hz, CH$_2$-2-naph), 4.65 (d, 2H, J = 12.5 Hz, CH$_2$-2-naph), 3.90-3.84 (m, 2H, CH-N=C)[22], 3.80 (pseudo dd, 2H, J = 9.4, 4.8 Hz, OCH$_2$-CH)[22], 3.62 (pseudo dd, 2H, J = 9.4, 6.6 Hz, OCH$_2$-CH)[22], 1.45 (s, 18H, t-Bu), 1.29 (s, 18H, t-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.90 (2C, CH=N), 158.41 (2C$_{ipso}$ α to OH), 139.84 (2C$_{ipso}$ α to t-Bu), 136.81 (2C$_{ipso}$ α to t-Bu), 135.50 (2C$_{ipso}$ of 2-naph), 133.20 (2C$_{ipso}$ of 2-naph), 132.93 (2C$_{ipso}$ of 2-naph), 128.15 (2CH of 2-naph), 127.91 (2CH of 2-naph), 127.64 (2CH of 2-naph), 127.17 (2C, CH of phenol), 126.34 (2CH of 2-naph), 126.14 (2C, CH of phenol),

126.05 (2CH of 2-naph), 125.83 (2CH of 2-naph), 125.58 (2CH of 2-naph), 117.72 ($2C_{ipso}$ α to imine), 73.34 (2C, $\underline{C}H_2$-2-naph), 70.91 (2C, O$\underline{C}H_2$-CH), 69.42 (2C, $\underline{C}$H-N=C), 35.08 (2C, $\underline{C}(CH_3)_3$), 34.10 (2C, $\underline{C}(CH_3)_3$), 31.49 (6C, C($\underline{C}H_3)_3$), 29.42 (6C, C($\underline{C}H_3)_3$); MS (FAB, *m*-nitrobenzylic alcohol matrix) ***m/z* (%)**: calcd for $C_{56}H_{68}N_2O_4$ 832.5 $[M]^+$, found 831 (32), 832 (74), 833 (100), 834 (49), 835 (16); $[\alpha]_D^{24}$ = +15.5, $[\alpha]_{578}^{24}$ = +16.2, $[\alpha]_{546}^{24}$ = +18.3 (c = 1.5, $CHCl_3$); Anal. Calcd for $C_{56}H_{68}N_2O_4$: C, 80.73; H, 8.23; N, 3.36. Found: C, 80.12; H, 8.23; N, 3.34.

(2S,3S)-N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(triphenylmethoxy)-2,3-diaminobutane (S,S)-5e

A suspension of (2*S*,3*S*)-1,4-bis(triphenylmethoxy)-2,3-diaminobutane (2*S*,3*S*)-**3e** (242 mg, 0.4 mmol) in distilled water (0.75 mL) and ethanol (3 mL) was heated at reflux until complete dissolution. A solution of 3,5-di-*tert*-butyl-2-hydroxybenzaldehyde **4** (188 mg, 0.8 mmol) in ethanol (2 mL) was added over 15 min *via* a syringe. The syringe was rinsed with ethanol (0.5 mL) and the yellow slurry was further stirred at reflux for 2 h. After evaporation of the solvents, the crude solid was redissolved in CH_2Cl_2 (4 mL) and washed with water (2 x 2 mL) and brine (1 mL). After drying over $MgSO_4$, the solvent was removed under vacuum and after chromatography on silica gel (gradient elution from petroleum ether to 2% *tert*-butyl methyl ether/petroleum ether), the pure salen ligand (2*S*,3*S*)-**5e** was isolated as a yellow foam (0.323 g, 78% yield); M.p. 101-103 °C; R_f = 0.19 with 1% ethyl acetate/petroleum ether; IR (Nujol, NaCl): ν 3085, 3059, 3023, 1739, 1629, 1598, 1452, 1363, 1272, 1249, 1074, 908, 770, 736, 704 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 13.55 (s, 2H, O$\underline{H}$), 8.38 (s, 2H, C$\underline{H}$=N), 7.35 (d, 2H, *J* = 2.4 Hz, C$\underline{H}$ of phenol), 7.34-7.28 (m, 12H of CPh_3), 7.21-7.13 (m, 18H of Tr), 7.05 (d, 2H, *J* = 2.4 Hz, C$\underline{H}$ of phenol), 3.73-3.66 (m, 2H, C$\underline{H}$-N=C)[22], 3.24 (pseudo dd, 2H, *J* = 9.5, 4.6 Hz, OC$\underline{H}_2$-CH)[22], 3.20 (pseudo dd, 2H, *J* = 9.5, 6.6 Hz, OC$\underline{H}_2$-CH)[22], 1.45 (s, 9H, *t*-Bu), 1.29 (s, 9H, *t*-Bu); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.87 (2C, $\underline{C}$H=N), 158.33 ($2C_{ipso}$ α to OH), 143.77 ($6C_{ipso}$ of Tr), 139.70 ($2C_{ipso}$ α to *t*-Bu), 136.59 ($2C_{ipso}$ α to *t*-Bu), 128.62 ($12C_{meta}$ of Tr), 127.78 ($12C_{ortho}$ of Tr), 126.97 (2C, $\underline{C}$H of phenol), 126.92 ($6C_{para}$ of Tr), 126.11 (2C, $\underline{C}$H of phenol), 117.71 ($2C_{ipso}$ α to imine), 86.79 (2C, $\underline{C}Ph_3$), 70.19 (2C, $\underline{C}$H-N=C), 64.07 (2C, O$\underline{C}H_2$-CH), 35.04 (2C, $\underline{C}(CH_3)_3$), 34.08 (2C, $\underline{C}(CH_3)_3$), 31.50 (6C, C($\underline{C}H_3)_3$), 29.41 (6C, C($\underline{C}H_3)_3$); $[\alpha]_D^{24}$ = +26.3, $[\alpha]_{578}^{24}$ = +27.5, $[\alpha]_{546}^{24}$ = +31.3 (c = 2.2, $CHCl_3$); HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{72}H_{81}N_2O_4$ 1037.6196 $[M+H]^+$, found 1037.6191 (2.4), calcd for $C_{72}H_{80}N_2O_4$ 1036.6118 $[M]^+$, found 1036.6142 (2.2), 1021.6 $[M-CH_3]^+$ (0.15), 794.5 $[M-CPh_3+H]^+$ (0.08), 777.5 $[M-OCPh_3]^+$ (0.04), 243.1 $[Ph_3C]^+$ (base peak); Anal. Calcd for $C_{72}H_{80}N_2O_4$: C, 83.36; H, 7.77; N, 2.70. Found: C, 82.86; H, 8.11; N, 2.66.

Data for the salen Mn(III) and salen Cr(III) complexes

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-dihydroxy-2,3-diaminobutane]manganese(III)chloride (S,S)-6a

A mixture of the salen ligand (2*S*,3*S*)-**5a** (100 mg, 0.18 mmol) and ethanol (4 mL) was heated at reflux for 25 min before the addition of a solution of $Mn(OAc)_2 \cdot 4H_2O$ (99 mg, 0.40 mmol) in water (1 mL) *via* syringe. The resulting brown solution was refluxed for 1 h. Reflux was continued for an additional 25 min while air was bubbled into the solution. After following the same procedure as described for (2*S*,3*S*)-**6c**, the crude salen Mn(III) complex was purified by column chromatography (gradient elution from CH_2Cl_2 to 10% MeOH/CH_2Cl_2) to afford the catalyst (2*S*,3*S*)-**6a** as a brown solid (88 mg, 76% yield); M.p. 172-173°C; R_f = 0.12 with 10% MeOH/CH_2Cl_2; IR (Nujol, NaCl): ν 3340 (broad), 1598, 1553, 1534, 1413, 1390, 1362, 1307, 1272, 1253, 1200, 1177, 842 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{34}H_{50}MnN_2O_4$ 605.3151 $[M-Cl]^+$, found 605.3145 (base peak), 640.3 $[M]^+$ (1.5); Anal. Calcd for $C_{34}H_{50}ClMnN_2O_4$: C, 63.69; H, 7.86; N, 4.37. Found: C, 64.14; H, 7.91; N, 3.83.

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-dimethoxy-2,3-diaminobutane]manganese(III)chloride (S,S)-6b

As described for (2*S*,3*S*)-**6c**, to a solution of salen ligand (2*S*,3*S*)-**5b** (160 mg, 0.27 mmol) in ethanol (12 mL) was added a solution of $Mn(OAc)_2 \cdot 4H_2O$ (113 mg, 0.45 mmol) in water (1 mL) followed by oxidation by air bubbling. After the same work-up, the crude salen Mn(III) complex was purified by column chromatography (gradient elution from CH_2Cl_2 to 5% ethanol/CH_2Cl_2) to afford the catalyst (2*S*,3*S*)-**6b** as a brown solid (157 mg, 86% yield); M.p. > 270 °C; R_f = 0.31 with 2% ethanol/CH_2Cl_2; IR (Nujol, NaCl): ν 1612, 1600, 1534, 1305, 1252, 1201, 1176, 1126, 842, 782 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{36}H_{54}MnN_2O_4$ 633.3464 $[M\text{-}Cl]^+$, found 633.3468 (base peak), calcd for $C_{36}H_{54}ClMnN_2O_4$ 668.3153 $[M]^+$, found 668.3158 (2); Anal. Calcd for $C_{36}H_{54}ClMnN_2O_4$: C, 64.61; H, 8.13. Found: C, 64.25; H, 8.31.

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(phenylmethoxy)-2,3-diaminobutane]manganese(III) chloride (S,S)-6c

A mixture of the salen ligand (2*S*,3*S*)-**5c** (440 mg, 0.6 mmol) and ethanol (33 mL) was heated at reflux for 15 min before the addition of a solution of $Mn(OAc)_2 \cdot 4H_2O$ (310 mg, 1.25 mmol) in water (2.75 mL). The resulting brown solution was refluxed for 45 min. Reflux was continued for an additional 15 min while air was bubbled into the solution. Brine (1.65 mL) was added and the mixtUre was refluxed for additional 30 min. After cooling to room temperature, the mixture was concentrated to remove ethanol. Methylene chloride (50 mL) and brine (50 mL) were added. The organic layer was separated, washed with distilled water (50 mL), and dried over $MgSO_4$. After concentration, the crude catalyst was purified by column chromatography (gradient elution from CH_2Cl_2 to 5% ethanol/CH_2Cl_2) to afford the catalyst (*S*,*S*)-**6c** as a brown solid (452 mg, 92% yield); M.p. > 270°C; R_f = 0.20 with 2% ethanol/CH_2Cl_2; IR (Nujol, NaCl): ν 3086, 3059, 3031, 1614, 1599, 1534, 1305, 1253, 1176, 1103, 840, 734, 697 cm^{-1}; MS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{48}H_{62}MnN_2O_4$ 785.4 $[M\text{-}Cl]^+$, found 784 (17), 785 (100), 786 (74), 787 (23); Anal. Calcd for $C_{48}H_{62}ClMnN_2O_4$: C, 70.19; H, 7.61; N, 3.41. Found: C, 69.83; H, 7.98; N, 3.25.

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis[(2-naphtyl)methoxy]-2,3-diaminobutane] manganese(III)chloride (S,S)-6d

As described for (2*S*,3*S*)-**6c**, to a solution of salen ligand (2*S*,3*S*)-**5d** (629 mg, 0.75 mmol) in ethanol (42 mL) was added a solution of $Mn(OAc)_2 \cdot 4H_2O$ (368 mg, 1.5 mmol) in water (3.5 mL) followed by oxidation by air bubbling. After the same work-up, the crude salen Mn(III) complex was purified by column chromatography (gradient elution from CH_2Cl_2 to 2% MeOH/CH_2Cl_2) to afford the catalyst (2*S*,3*S*)-**6b** as a brown solid (566 mg, 82% yield); M.p. > 270 °C; R_f = 0.15 with 1% MeOH/CH_2Cl_2; IR (Nujol, NaCl): ν 3052, 1607, 1533, 1305, 1251, 1175, 1094, 1033, 840, 823 cm^{-1}; MS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{56}H_{66}MnN_2O_4$ 885.4 $[M\text{-}Cl]^+$, found 884 (8), 885 (100), 886 (62), 887 (21); Anal. Calcd for $C_{56}H_{66}ClMnN_2O_4$: C, 72.99; H, 7.22; N, 3.04. Found: C, 72.74; H, 7.15; N, 2.88.

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(triphenylmethoxy)-2,3-diaminobutane] manganese(III)chloride (S,S)-6e

As described for (2*S*,3*S*)-**6c**, to a solution of salen ligand (2*S*,3*S*)-**5e** (0.256 g, 0.24 mmol) in ethanol (14 mL) was added a solution of $Mn(OAc)_2 \cdot 4H_2O$ (128 mg, 0.52 mmol) in water (1.2 mL) followed by oxidation by air bubbling. After the same work-up, the crude salen Mn(III) complex was purified by column chromatography (gradient elution from CH_2Cl_2 to 1% MeOH/CH_2Cl_2) to afford the catalyst (2*S*,3*S*)-**6e** as a brown solid (218 mg, 81% yield); M.p. > 163-165 °C; R_f = 0.12 with CH_2Cl_2; IR (Nujol, NaCl): ν 3056, 1731, 1600, 1533, 1309, 1252, 1176, 1075, 840, 705 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{72}H_{78}MnN_2O_4$ 1089.5342 $[M\text{-}Cl]^+$, found 1089.5344 (10.5), 1124 $[M]^+$ (0.3), 847.4 $[M\text{-}CPh_3+H]^+$ (0.5), 816.4 $[M\text{-}CH_2OCPh_3]^+$ (0.4), 243.1 $[Ph_3C]^+$ (base peak); Anal. Calcd for $C_{72}H_{78}ClMnN_2O_4$: C, 76.81; H, 6.98; N, 2.49. Found: C, 76.31; H, 6.94; N, 2.35.

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(phenylmethoxy)-2,3-diaminobutane]chromium(III) hexafluorophosphate (S,S)-22a

A dark brown solution of the salen ligand (2*S*,3*S*)-**6c** (290 mg, 0.4 mmol) and anhydrous $CrCl_2$ (60 mg, 0.45 mmol) in dry, degassed THF (8 mL) was stirred for 3.5 h under N_2 and then for another 3 h under an oxygene atmosphere. After dilution with *tert*-butyl methyl ether (50 mL), the resulting solution was washed with saturated NH_4Cl (3 x 25 mL), brine (3 x 25 mL) and dried over anhydrous $MgSO_4$. Concentration afforded crude (2*S*,3*S*)-[*N*,*N*'-bis(3,5-di-tert-butylsalicylidene)-1,4-bis(phenylmethoxy)-2,3-diaminobutane]chromium (III) chloride as a deep brown solid (288 mg, 88%); M.p. >115 °C (dec.); IR (Nujol, NaCl): ν 3086, 3061, 3030, 1610, 1530, 1321, 1170, 1100, 840, 735, 699 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) ***m/z*** **(%)**: calcd for $C_{48}H_{62}{}^{35}Cl^{52}CrN_2O_4$ 817.3803 $[M]^+$, found 817.3796 (2.0), 782.4 $[M\text{-}Cl]^+$ (base peak), 691.4 $[M\text{-}Cl\text{-}CH_2Ph]^+$ (7.0), 540.4 $[M\text{-}Cl\text{-}2\ CH_2OCH_2Ph]^+$ (22.4), 525.3 $[M\text{-}Cl\text{-}2\ CH_2OCH_2Ph\text{-}CH_3]^+$ (8.0). To a solution of $AgPF_6$ (53 mg, 0.21 mmol) in dry CH_3CN (0.6 mL), the salen Cr(III)-chloride complex (164 mg, 0.20 mmol) in dry CH_3CN (0.4 mL) was added dropwise *via* a microsyringe. During the addition, the beginning of precipitation of AgCl from the brown mixture was observed. This heterogeneous mixture was stirred for another 20 h in the absence of daylight and then filtered through a pad of Celite and washed with CH_3CN (2 x 2 mL). This filtrate was concentrated to afford the title salen Cr(III)-hexafluorophosphate complex (2*S*,3*S*)-**22a** as a brown-orange powder (165 mg, 89%); M.p. 149-151 °C; IR (Nujol, NaCl): ν 3086, 3061, 1608, 1532, 1365, 1315, 1272, 1254, 1172, 1096, 841, 738, 700 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{48}H_{62}{}^{52}CrN_2O_4$ 782.4115 $[M\text{-}PF_6]^+$, found 782.4154 (base peak), 767.3 $[M\text{-}PF_6\text{-}CH_3]^+$ (4.1), 691.3 $[M\text{-}PF_6\text{-}CH_2Ph]^+$ (8.6), 540.1 $[M\text{-}PF_6\text{-}2\ CH_2OCH_2Ph]^+$ (41.0), 525.1 $[M\text{-}PF_6\text{-}2\ CH_2OCH_2Ph\text{-}CH_3]^+$ (17.6).

(2S,3S)-[N,N'-Bis(3,5-di-tert-butylsalicylidene)-1,4-bis(phenylmethoxy)-2,3-diaminobutane]chromium(III) trifluoromethanesulfonate (S,S)-22b

As described for (2*S*,3*S*)-**22a**, to a solution of AgOTf (27 mg, 0.105 mmol) in dry CH_3CN (0.3 mL), salen Cr(III)-chloride complex (82 mg, 0.1 mmol) in dry CH_3CN (0.2 mL) was added dropwise and after workup trifluoromethanesulfonate complex (2*S*,3*S*)-**22b** (deep brown powder, 86 mg, 92%) was isolated; M.p. >105 °C (dec.); IR (Nujol, NaCl): ν 3064, 3030, 1605, 1533, 1170, 1029, 879, 841, 737, 699 cm^{-1}; HRMS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{49}H_{62}CrF_3N_2O_7S$ 931.3635 $[M]^+$, found 931.3644 (3); MS (FAB, *m*-nitrobenzylic alcohol matrix) *m/z* (%): calcd for $C_{48}H_{62}CrN_2O_4$ 782.4 $[M\text{-}OTf]^+$, found 782.4 (base peak), 691.4 $[M\text{-}OTf\text{-}CH_2Ph]^+$ (8.8), 540.3 $[M\text{-}\ OTf\ \text{-}2\ CH_2OCH_2Ph]^+$ (34.3), 525.3 $[M\text{-}\ OTf\ \text{-}2\ CH_2OCH_2Ph\text{-}CH_3]^+$ (13.5).

Typical experimental procedures for asymmetric epoxidations catalyzed with (*S,S*)-6

a) Using NaOCl/4-PPNO:

A solution of commercial household bleach (ca. 2.1 M) was buffered to pH = 11.3 with 0.05 M NaH_2PO_4 and 1 N NaOH and then cooled to 0 °C. To this solution (1.85 mL, approximately 0.55 M in NaOCl) was added a solution of olefin **7**, **9**-**15**[23] (0.5 mmol), catalyst (*S,S*)-**6** (0.02 mmol) and 4-PPNO (0.1 mmol) in CH_2Cl_2 (0.5 mL). The two-phase system was mechanically stirred at 0 °C and the progress of the reaction was monitored by TLC. After stirring for the indicated time in table 2, the heterogeneous brown mixture was filtered through a pad of celite and the organic phase was separated, washed once with brine (1.85 mL), and then dried over $MgSO_4$. After concentration, the crude product was purified by flash chromatography on silica gel.

b) Using MCPBA/NMO•H_2O:

A round bottom flask was charged with the olefin **7**, **9**-**15**[23] (0.5 mmol), dry CH_2Cl_2 (4.25 mL), catalyst (*S,S*)-**6** (0.02 mmol) and NMO•H_2O (2.5 mmol). This solution was cooled to –78 °C (color turned from deep brown to brown-yellow) before the addition of precooled, solid MCPBA (1.0 mmol) in two roughly equal portions. The reaction mixture was monitored by TLC. Upon consumption of the olefin, the reaction mixture

was quenched by addition of dimethyl sulfide (2.5 mmol). A solution of 2 N NaOH (5 mL) was then added, and the organic layer was separated, washed with distilled water, and dried over $MgSO_4$. After concentration, the crude product was purified by flash chromatography on silica gel.

c) Determination of % ee:

Enantiomeric excesses were determined by ^1H NMR analysis of a solution of 6-7 mg (0.03-0.04 mmol) of epoxide and the same amount (0.005-0.006 mmol) of (+)-Eu(hfc)$_3$ in $CDCl_3$ (0.7 mL). In the case of chromene derivatives, the more deshielded methyl signal gave the bigger splitting of singlets, hence affording the more accurate determination of % ee.

Experimental procedure for asymmetric epoxidation catalyzed with (*S,S*)-22a

Iodosylbenzene (222 mg, 1 mmol) was added in one portion to a solution of the olefin **7** (80 mg, 0.5 mmol), catalyst (*S,S*)-**22a** (46 mg, 0.05 mmol), and $OPPh_3$ (28 mg, 0.1 mmol) in CH_3CN (2.5 mL) at 0 °C. The reaction was monitored by TLC. Upon consumption of the olefin, the reaction mixture was concentrated *in vacuo* and the crude product was purified by flash chromatography on silica gel.

Data for the epoxides

3,4-Epoxy-2,2-dimethylchromane 8

Slightly yellow oil; R_f = 0.19 with 10% ethyl acetate/petroleum ether; IR (neat, NaCl): ν 3055, 2980, 2933, 2876, 1614, 1587, 1491, 1473, 1366, 1270, 1239, 1207, 1165, 1040, 957, 915, 906, 754 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.33 (broad dd, 1H, $J_{5,6}$ = 7.4 Hz, $J_{5,7}$ = 1.7 Hz, broadening is due to para coupling $J_{5,8}$, H-C_5), 7.24 (ddd, 1H, $J_{7,8}$ = 8.1 Hz, $J_{6,7}$ = 7.4 Hz, $J_{5,7}$ = 1.7 Hz, H-C_7), 6.93 (ddd, 1H, $J_{5,6}$ = $J_{6,7}$ = 7.4 Hz, $J_{6,8}$ = 1.1 Hz, H-C_6), 6.81 (ddd, 1H, $J_{7,8}$ = 8.1 Hz, $J_{6,8}$ = 1.1 Hz, $J_{5,8}$ = 0.6 Hz, H-C_8), 3.90 (d, 1H, $J_{3,4}$ = 4.4 Hz, H-C_4), 3.50 (d, 1H, $J_{3,4}$ = 4.4 Hz, H-C_3), 1.58 (s, 3H, $C\underline{H}_3$), 1.25 (s, 3H, $C\underline{H}_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.56 (C_{8a}), 130.30 (C_7), 129.64 (C_5), 121.07 (C_6), 119.93 (C_{4a}), 118.01 (C_8), 72.99 (C_2), 62.88 (C_3), 51.00 (C_4), 25.69 ($\underline{C}H_3$, correlates with protons at 1.58 ppm), 22.59 ($\underline{C}H_3$, correlates with protons at 1.25 ppm); Optical rotation of the sample obtained by use of MCPBA/NMO•H_2O as terminal oxidant (69% ee): $[\alpha]_D^{25}$ = -18.6, $[\alpha]_{578}^{25}$ = -19.5, $[\alpha]_{546}^{25}$ = -20.9, $[\alpha]_{436}^{25}$ = -23.4, (c = 0.56, THF); lit.[10] for (*3S,4S*)-(-)-3,4-epoxy-2,2-dimethylchromane: $[\alpha]_D$ = -31, (c = 0.47, THF).

6-Cyano-3,4-epoxy-2,2-dimethylchromane 16

Slightly yellow oil which crystallized after prolonged storage in the refrigerator yielding cream-colored crystals melting at 135-138 °C; R_f = 0.25 with 20% ethyl acetate/petroleum ether; IR (neat, NaCl): ν 2983, 2935, 2227, 1616, 1580, 1495, 1280, 1208, 1163, 958, 868 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.66 (d, 1H, $J_{5,7}$ = 2.0 Hz, H-C_5), 7.53 (dd, 1H, $J_{7,8}$ = 8.5 Hz, $J_{5,7}$ = 2.0 Hz, H-C_7), 6.87 (d, 1H, $J_{7,8}$ = 8.5 Hz, H-C_8), 3.92 (d, 1H, $J_{3,4}$ = 4.2 Hz, H-C_4), 3.55 (d, 1H, $J_{3,4}$ = 4.2 Hz, H-C_3), 1.60 (s, 3H, $C\underline{H}_3$), 1.30 (s, 3H, $C\underline{H}_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 156.49 (C_{8a}), 134.41 (C_7), 133.82 (C_5), 121.11 (C_{4a}), 119.03 (C_8), 119.01 (C_6)[24], 104.28 ($\underline{C}N$), 74.68 (C_2), 62.30 (C_3), 49.88 (C_4), 25.49 ($\underline{C}H_3$, correlates with protons at 1.60 ppm), 23.02 ($\underline{C}H_3$, correlates with protons at 1.30 ppm); Optical rotation of the sample obtained by use of MCPBA/NMO•H_2O as terminal oxidant (50% ee): $[\alpha]_D^{25}$ = -29.7, $[\alpha]_{578}^{25}$ = -30.8, $[\alpha]_{546}^{25}$ = -35.0, (c = 0.74, $CHCl_3$); lit.[25a] for (*3S,4S*)-(-)-6-cyano-3,4-epoxy-2,2-dimethylchromane (93% ee): $[\alpha]_D$ = -55.8, (c ≈ 1, $CHCl_3$). We checked that catalyzed epoxidation of **9** by (*R,R*)-**1** using MCPBA/NMO•H_2O as terminal oxidant afforded (*3R,4R*)-(+)-6-cyano-3,4-epoxy-2,2-dimethylchromane (≥ 97% ee) with $[\alpha]_D^{23}$ = +62.5, $[\alpha]_{578}^{23}$ = +65, $[\alpha]_{546}^{23}$ = +74, $[\alpha]_{436}^{23}$ = +121, $[\alpha]_{365}^{23}$ = +163 (c = 0.94, $CHCl_3$).

6-Nitro-3,4-epoxy-2,2-dimethylchromane 17

White crystals; M.p. 88-90 °C; R_f= 0.26 with 20% ethyl acetate/petroleum ether; IR (neat, NaCl): ν 3076, 2928, 2855, 1619, 1592, 1522, 1345, 1282, 1209, 1159, 1090, 955, 909, 874, 828, 744, 689 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 8.30 (d, 1H, $J_{5,7}$ = 2.7 Hz, H-C_5), 8.15 (dd, 1H, $J_{7,8}$ = 9.0 Hz, $J_{5,7}$ = 2.7 Hz, H-C_7), 6.89 (d, 1H, $J_{7,8}$ = 9.0 Hz, H-C_8), 3.99 (d, 1H, $J_{3,4}$ = 4.3 Hz, H-C_4), 3.57 (d, 1H, $J_{3,4}$ = 4.3 Hz, H-C_3), 1.62 (s, 3H, $C\underline{H}_3$), 1.33 (s, 3H, $C\underline{H}_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.30 (C_{8a}), 141.43 (C_6), 126.30 (C_7), 125.82 (C_5), 120.29 (C_{4a}), 118.49 (C_8), 75.21 (C_2), 62.10 (C_3), 50.04 (C_4), 25.46 ($\underline{C}H_3$, correlates with protons at 1.62 ppm), 23.14 ($\underline{C}H_3$, correlates with protons at 1.33 ppm); Optical rotation of the sample obtained by use of MCPBA/NMO•H_2O as terminal oxidant (52% ee): $[\alpha]_D^{25}$ = -55.2, $[\alpha]_{578}^{25}$ = -59, $[\alpha]_{546}^{25}$ = -71, $[\alpha]_{436}^{25}$ = -196, (c = 0.5, $CHCl_3$).

6-Chloro-3,4-epoxy-2,2-dimethylchromane 18

Slightly yellow oil; R_f= 0.22 with 10% ethyl acetate/petroleum ether;
IR (neat, NaCl): ν 2983, 2934, 1609, 1579, 1481, 1367, 1339, 1269, 1235, 1204, 1165, 1104, 1085, 1039, 956, 922, 860, 821, 763, 700 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.31 (d, 1H, $J_{5,7}$ = 2.6 Hz, H-C_5), 7.18 (dd, 1H, $J_{7,8}$ = 8.7 Hz, $J_{5,7}$ = 2.6 Hz, H-C_7), 6.74 (dd, 1H, $J_{7,8}$ = 8.7 Hz, $J_{4,8}$ = 0.4 Hz, H-C_8), 3.84 (dd, 1H, $J_{3,4}$ = 4.4 Hz, $J_{4,8}$ = 0.4 Hz, H-C_4), 3.48 (d, 1H, $J_{3,4}$ = 4.4 Hz, H-C_3), 1.57 (s, 3H, $C\underline{H}_3$), 1.24 (s, 3H, $C\underline{H}_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.18 (C_{8a}), 130.14 (C_7), 129.23 (C_5), 125.62 and 121.59 (C_{4a} and C_6), 119.39 (C_8), 73.38 (C_2), 62.54 (C_3), 50.39 (C_4), 25.57 ($\underline{C}H_3$, correlates with protons at 1.57 ppm), 22.49 ($\underline{C}H_3$, correlates with protons at 1.24 ppm); HRMS (EI, 70 eV) *m/z* (%): calcd for $C_{11}H_{11}{}^{35}ClO_2$ 210.0447 $[M]^+$, found 210.0440 (38.7), 195 $[M\text{-}Me]^+$ (2.0), 179 (11.0), 154 (base peak); Optical rotation of the sample obtained by use of NaOCl/4-PPNO as terminal oxidant (53% ee): $[\alpha]_D^{28}$ = -16.7, $[\alpha]_{578}^{28}$ = -17.2, $[\alpha]_{546}^{28}$ = -18.9, $[\alpha]_{436}^{28}$ = -23.4, (c = 1.1, $CHCl_3$).

6-Methoxy-3,4-epoxy-2,2-dimethylchromane 19

White crystals; M.p. 63-65 °C; R_f = 0.15 with 10% ethyl acetate/petroleum ether; IR (Nujol, NaCl): ν 3052, 3004, 2979, 1889, 1732, 1615, 1499, 1366, 1315, 1262, 1190, 1170, 1158, 1030, 956, 938, 913, 868, 856, 836, 825, 768, 738 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 6.89 (dd, 1H, $J_{5,7}$ = 2.9 Hz, $J_{5,8}$ = 0.5 Hz, H-C_5), 6.79 (dd, 1H, $J_{7,8}$ = 8.8 Hz, $J_{5,7}$ = 2.9 Hz, H-C_7), 6.74 (ddd, 1H, $J_{7,8}$ = 8.8 Hz, $J_{5,8}$ = 0.5 Hz, $J_{4,8}$ = 0.5 Hz, H-C_8), 3.86 (dd, 1H, $J_{3,4}$ = 4.4 Hz, $J_{4,8}$ = 0.5 Hz, H-C_4), 3.78 (s, 3H, $OC\underline{H}_3$), 3.46 (d, 1H, $J_{3,4}$ = 4.4 Hz, H-C_3), 1.56 (s, 3H, $C\underline{H}_3$), 1.22 (s, 3H, $C\underline{H}_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.84 (C_6), 146.22 (C_{8a}), 120.66 (C_{4a}), 118.73 (C_8), 115.62 (C_7), 114.67 (C_5), 72.68 (C_2), 62.76 (C_3), 55.75 ($O\underline{C}H_3$), 51.13 (C_4), 25.68 ($\underline{C}H_3$, correlates with protons at 1.56 ppm), 22.26 ($\underline{C}H_3$, correlates with protons at 1.22 ppm); Optical rotation of the sample obtained by use of MCPBA/NMO•H_2O as terminal oxidant (64% ee): $[\alpha]_D^{26}$ = -5.4, $[\alpha]_{578}^{26}$ = -6.3, $[\alpha]_{546}^{26}$ = -5.9, $[\alpha]_{436}^{26}$ = 5.7, (c = 0.54, $CHCl_3$).

1,2-Epoxy-1,2,3,4-tetrahydronaphthalene 20

White crystals; M.p. 44 °C; R_f = 0.4 with 10% ethyl acetate/petroleum ether; IR (neat, NaCl): ν 3047, 3012, 2999, 2934, 2850, 1494, 1467, 1433, 1278, 937, 894, 853, 796, 759, 747, 730 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.39 (broad dd, 1H, $J_{7,8}$ = 7.3 Hz, $J_{6,8}$ = 1.5 Hz, broadening is due to para coupling $J_{5,8}$, H-C_8), 7.25 (ddd, 1H, $J_{7,8}$ = 7.4 Hz, $J_{6,7}$ = 7.4 Hz, $J_{5,7}$ = 1.6 Hz, H-C_7), 7.20 (dddd, 1H, $J_{6,7}$ = 7.4 Hz, $J_{5,6}$ = 7.3 Hz, $J_{6,8}$ = 1.5 Hz, $J_{4a,6}$ = 1.0 Hz, H-C_6), 7.09 (broad ddd, 1H, $J_{5,6}$ = 7.3 Hz, $J_{5,7}$ = 1.6 Hz, $J_{4a,5}$ = 1.1 Hz, broadening is due to para coupling $J_{5,8}$, H-C_5), 3.84 (d, 1H, $J_{1,2}$ = 4.1 Hz, H-C_1), 3.73 (dddd, 1H, $J_{1,2}$ = 4.1 Hz, $J_{2,3e}$ = 3.0 Hz, $J_{2,4e}$ = 1.2 Hz, $J_{2,3a}$ = 0.8 Hz, H-C_2), 2.78 (ddddd, 1H, $J_{4a,4e}$ = 15.5 Hz, $J_{3a,4a}$ = 13.3 Hz, $J_{3e,4a}$ = 6.5 Hz, $J_{4a,5}$ = 1.1 Hz, $J_{4a,6}$ = 1.0 Hz, H_a-C_4), 2.54 (dddd, 1H, $J_{4a,4e}$ = 15.5 Hz, $J_{3a,4e}$ = 5.6 Hz, $J_{3e,4e}$ = 1.6 Hz, $J_{2,4e}$ = 1.2 Hz, H_e-C_4), 2.41 (dddd, 1H, $J_{3a,3e}$ = 14.4 Hz, $J_{3e,4a}$ = 6.5 Hz, $J_{2,3e}$ = 3.0 Hz, $J_{3e,4e}$ = 1.6 Hz, H_e-C_3), 1.76 (dddd, 1H, $J_{3a,3e}$ = 14.4 Hz, $J_{3a,4a}$ = 13.3 Hz, $J_{3a,4e}$ = 5.6 Hz, $J_{2,3a}$ = 0.8 Hz, H_a-C_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.67 (C_{ipso}), 132.52 (C_{ipso}), 129.53 (C_8), 128.42 and 128.39 (C_5 and C_7), 126.10 (C_6), 55.10 (C_2), 52.75 (C_1), 24.37 (C_4), 21.79 (C_3); Optical rotation of the sample

obtained by use of MCPBA/NMO·H_2O as terminal oxidant (50% ee): $[\alpha]_D^{25}$ = -60, $[\alpha]_{578}^{25}$ = **-63**, $[\alpha]_{546}^{25}$ = -72, $[\alpha]_{436}^{25}$ = -124, (c = 0.84, $CHCl_3$); lit.[25b] for (1*R*,2*S*)-(+)-1,2-epoxy-1,2,3,4-tetrahydronaphthalene: $[\alpha]_D$ = +135, ($CHCl_3$).

1,2-Epoxyindane 21

Slightly yellow oil; R_f = 0.31 with 10% ethyl acetate/petroleum ether; IR (neat, NaCl): ν 3044, 3030, 2913, 2821, 1473, 1467, 1419, 1372, 1229, 1000, 983, 828, 759, 723 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): δ 7.50 (broad d, 1H, $J_{6,7}$ = 7.3 Hz, H-C_7), 7.29-7.17 (m, 3H, H-$C_{4,5,6}$), 4.27 (dd, 1H, $J_{1,2}$ = 2.8 Hz, $J_{1,4}$ = 1.2 Hz, H-C_1), 4.14 (dd, 1H, $J_{2,3b}$ = 3.0 Hz, $J_{1,2}$ = 2.8 Hz, H-C_2), 3.22 (broad d, 1H, $J_{3a,3b}$ = 18.0 Hz, bradening is due to $J_{3,4}$ and $J_{3,5}$, H_a-C_3), 2.99 (dd, 1H, $J_{3a,3b}$ = 18.0 Hz, $J_{2,3b}$ = 3.0 Hz, H_b-C_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.49 (C_{ipso}), 140.80 (C_{ipso}), 128.50, 126.17, and 126.03 ($C_{4,5,6}$), 125.13 (C_7), 59.07 (C_1), 57.63 (C_2), 34.55 (C_3). Due to the poor stability of this compound, optical rotation was found to be erratic. Thus, the absolute configuration of the major enantiomer was established by ^1H NMR analysis in $CDCl_3$ using Eu(hfc)$_3$ to be opposite of that of a standard (1*R*,2*S*)-epoxide[4] prepared using (*R*,*R*)-**1** (comparaison of spectra of mixtures in several proportions).

ACKNOWLEDGEMENTS

Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged. We also would like to thank Dr Florent Yvergnaux (I.R.T.L.) for the use of a cold room, Mr Hervé Léon and Mrs Isabelle Plessis for their help during training periods (respectively Maîtrise and D.E.S.S.), Mr Christophe Duriez (UMR 6510) for a chiral HPLC analysis, and the Centre Régional de Mesures Physiques de l'Ouest for mass spectral analysis.

REFERENCES AND NOTES

1. a) Zhang, W.; Loebach, J. L.; Wilson, S. R.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1990**, *112*, 2801-2803. b) Jacobsen, E. N. In: *Catalytic Asymmetric Synthesis*, Ojima, I., Ed., VCH; New York, **1993**, pp. 159-202. c) Irie, R.; Noda, K.; Ito, Y.; Matsumoto, N.; Katsuki, T. *Tetrahedron Lett.* **1990**, *31*, 7345-7348. d) Hosoya, N.; Hatayama, A.; Irie, R.; Sasaki, H.; Katsuki, T. *Tetrahedron* **1994**, *50*, 4311-4322. e) Katsuki, T. *Coord. Chem. Rev.* **1995**, *140*, 189-214.
2. Zhang, W. Ph. D. thesis, University of Illinois; September **1991**.
3. a) Synthesis of (2*S*,3*S*)-**3a,c**: Scheurer, A.; Mosset, P.; Saalfrank, R. W. *Tetrahedron: Asymmetry* **1997**, *8*, 1243-1251 and 3161. b) Synthesis of (2*S*,3*S*)-**3b,d,e**: Scheurer, A.; Mosset, P.; Saalfrank, R. W. *unpublished results*.
4. Pospisil, P. J.; Carsten, D. H.; Jacobsen, E. N. *Chem. Eur. J.* **1996**, *2*, 974-980.
5. Deng, L.; Jacobsen, E. N. *J. Org. Chem.* **1992**, *57*, 4320-4323.
6. Palucki, M.; McCormick, G. J.; Jacobsen, E. N. *Tetrahedron Lett.* **1995**, *36*, 5457-5460.
7. Pietikäinen, P. *Tetrahedron Lett.* **1995**, *36*, 319-322.
8. Fernández, I.; Pedro, J. R.; de la Salud, R. *Tetrahedron* **1996**, *52*, 12031-12038.
9. a)Yamada, T.; Takai, T.; Rhode, O.; Mukaiyama, T. *Chem. Lett.* **1991**, 1-4. b) Mukaiyama, T.; Yamada, T. *Bull. Soc. Chim. Jpn.* **1995**, *68*, 17-35.
10. Boyd, D. R.; Sharma, N. D.; Boyle, R.; Evans, T. A.; Malone, J. F.; McCombe, K. M.; Dalton, H.; Chima, J. *J. Chem. Soc., Perkin Trans. 1* **1996**, 1757-1765.
11. Optical rotations were reported for the following epoxides of known absolute configuration: (3*R*,4*R*)-(+)-3,4-epoxy-2,2-dimethylchromane,[10] (3*R*,4*R*)-(+)-6-cyano-3,4-epoxy-2,2-dimethylchromane,[25a]

(3*S*,4*S*)-(-)-6-cyano-3,4-epoxy-2,2-dimethylchromane,[25a] (1*R*,2*S*)-(+)-1,2-epoxy-1,2,3,4-tetrahydronaphtalen,[25b] and (1*R*,2*S*)-(-)-1,2-epoxyindane.[25c,d]

12. The change from (*R*,*R*) of **1** and **2** to (*S*,*S*) in **6** is only due to the definition of the absolute configuration following the Cahn-Ingold-Prelog rules.
13. a) Lee, N. H.; Muci, A. R.; Jacobsen, E. N. *Tetrahedron Lett.* **1991**, *32*, 5055-5058. b) Hosoya, N.; Hatayama, A.; Yanai, K.; Fujii, H.; Irie, R.; Katsuki, T. *Synlett* **1993**, 641-645.
14. For other results with more bulky catalysts, see ref. 1d) and 26.
15. A first reversal in stereochemistry of asymmetric epoxidation by an unsual solvent-effect using a salen Cr(III) complex as a catalyst was recently reported by Imanishi and Katsuki.[27]
16. Hughes, D. L.; Smith, G. B.; Liu, J.; Dezeny, G. C.; Senanayake, C. H.; Larsen, R. D.; Verhoeven, T. R.; Reider, P. J. *J. Org. Chem.* **1997**, *62*, 2222-2229.
17. To observe this reversal of enantioselectivity, it seems essential that the oxygen functionality is alicyclic since a salen Mn(III) catalyst bearing a THF moiety gave the same enantioselectivity[28] as Jacobsen and Katsuki catalysts.
18. Very recently, Katsuki and Ito reported a reversal of enantioselectivity by using a salen Mn(III) catalyst having a carboxylate group on the ethylenediamine moiety.[29]
19. With a batch of bleach, the formation of a side product arising from chlorination of the aromatic ring ((3*S*,4*S*)-6-chloro-3,4-epoxy-2,2-dimethylchromane) was also observed.
20. Bousquet, C.; Gilheany, D. G. *Tetrahedron Lett.* **1995**, *36*, 7739-7742.
21. a) Martínez, L. E.; Leighton, J. L.; Carsten, D. H.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1995**, *117*, 5897-5898. b) Leighton, J. L.; Jacobsen, E. N. *J. Org. Chem.* **1996**, *61*, 389-390.
22. A symmetrical six spins ABCC'A'B' system was observed (Table 6; for other examples, see ref. 3).

Table 6. Chemical shifts and non equal to zero coupling constants of the ABCC'A'B' system observed in ^{1}H NMR spectra of the salen derivatives (*S*,*S*)-**5a-e** in $CDCl_3$.

Compound	(*S*,*S*)-**5a**	(*S*,*S*)-**5b**	(*S*,*S*)-**5c**	(*S*,*S*)-**5d**	(*S*,*S*)-**5e**
$\delta_A = \delta_{A'}$ (ppm)	3.866	3.482	3.557	3.621	3.200
$\delta_B = \delta_{B'}$ (ppm)	3.925	3.665	3.745	3.805	3.232
$\delta_C = \delta_{C'}$ (ppm)	3.644	3.746	3.832	3.871	3.697
$J_{AB} = J_{A'B'}$ (Hz)	- 11.2	-9.6	- 9.5	- 9.5	- 9.5
$J_{AC} = J_{A'C'}$ (Hz)	6.9	7.0	6.5	6.7	6.8
$J_{BC} = J_{B'C'}$ (Hz)	4.0	4.9	5.0	4.8	4.4
$J_{CC'}$ (Hz)	5.9	4.5	4.3	4.5	6.0

23. 2,2-Dimethylchromene **7** was prepared by reduction of 2,2-dimethylchromanone[30a] with sodium borohydride in ethanol/THF followed by dehydration under Dean-Stark conditions (refluxing toluene, 0.03 equiv of TsOH•H_2O). 6-Cyano-, 6-nitro-, and 6-chloro-2,2-dimethylchromenes **9-11** were prepared by thermal rearrangement of aryl propargyl ethers.[30b] 6-Methoxy-2,2-dimethylchromene **12** was prepared using the procedure described for precocene I **13** however in low yield (14%).[30c]
24. ^{13}C NMR of 6-cyano-3,4-epoxy-2,2-dimethylchromane **16** in CD_3COCD_3 showed distinct signals for C_6 and C_8 at 119.24 and 119.58 ppm, respectively.
25. a) Adam, W.; Jeko, J.; Lévai, A.; Nemes, C.; Patonay, T.; Sebök, P. *Tetrahedron Lett.* **1995**, *36*, 3669-3672. b) Akhtar, M. N.; Boyd, D. R.; Hamilton, J. G. *J. Chem. Soc., Perkin Trans. 1* **1979**, 2437-2440. c) Boyd, D. R.; Sharma, N. D.; Bowers, N. I.; Goodrich, P. A.; Groocock, M. R.; Blacker, A. J.; Clarke, D. A.; Howard, T.; Dalton, H. *Tetrahedron: Asymmetry* **1996**, *7*, 1559-1562. d) Mitrochkine, A.; Eydoux, F.; Martres, M.; Gil, G.; Heumann, A.; Réglier, M. *Tetrahedron: Asymmetry* **1995**, *6*, 59-62.
26. Sasaki, H.; Irie, R.; Hamada, T.; Suzuki, K.; Katsuki, T. *Tetrahedron* **1994**, *50*, 11827-11838.

27. Imanishi, H.; Katsuki, T. *Tetrahedron Lett.* **1997**, *38*, 251-254.
28. a) Bell, D.; Miller, D.; Attrill, R. P. *PCT Int. Appl.* **WO 94/03271**. b) Bell, D.; Finney, F.; Attrill, R. P. Miller, D. *PCT Int. Appl.* **WO 95/21172**.
29. Ito, Y. N.; Katsuki, T. *Tetrahedron Lett.* **1998**, *39*, 4325-4328.
30. a) Analogous reaction with cyclohexanone: Bergmann, R.; Gericke, R. *J. Med. Chem.* **1990**, *33*, 492-504. b) Bell, D.; Davies, M. R.; Geen, G. R.; Mann, I. S. *Synthesis* **1995**, 707-712. c) Bissada, S.; Lau, C. K.; Bernstein, M. A.; Dufresne, C. *Can. J. Chem.* **1994**, *72*, 1866-1869.