Supporting Information

Direct Catalytic Asymmetric Michael Reaction of Hydroxyketones: Asymmetric Zn Catalysis with Et₂Zn/linked-BINOL Complex (2)

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Experimental Section

General.

Infrared (IR) spectra were recorded on a JASCO FT/IR 410 Fourier transform infrared spectrophotometer. NMR spectra were recorded on a JEOL JNM-LA500 spectrometer, operating at 500 MHz for ¹H NMR and 125.65 MHz for ¹³C NMR. Chemical shifts in CDCl₃ were reported downfield from TMS (= 0) or in the scale relative to CHCl₃ (7.24 ppm) for ¹H NMR. For ¹³C NMR, chemical shifts were reported in the scale relative to CHCl₃ (77.0 ppm) for ¹³C NMR as an internal reference. Chemical shifts in C₆D₆ were reported downfield from TMS (= 0) or in the scale relative to C₆D₆ (7.15 ppm) for ¹H NMR. For ¹³C NMR, chemical shifts were reported in the scale relative to C₆D₆ (128.0 ppm) for ¹³C NMR as an internal reference. Column chromatography was performed with silica gel Merck 60 (230–400 mesh ASTM). Optical rotations were measured on a JASCO P-1010 polarimeter. EI and FAB mass spectra were measured on JMS-BU20 GCmate. ESI mass spectra were measured on Waters micromass ZQ. The enantiomeric excess (ee) was determined by HPLC analysis. HPLC was performed on JASCO HPLC systems consisting of the following: pump, 880-PU or PU-980; detector, 875-UV or UV-970, measured at 254 nm; column, DAICEL CHIRALCEL OD, OD-H, OJ, OJ-H, CHIRALPAK AD, AD-H, AS, AS-H; mobile phase, hexane–2-propanol. Reactions were carried out in dry solvents under argon atmosphere, unless otherwise stated. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl. Et₂Zn (1.0 M, in hexanes) was purchased from Aldrich, which was titrated prior to use. Other reagents were purified by the usual methods.

(A) First generation Et₂Zn/(*S,S*)-linked-BINOL **1** = 2/1 complex:

General Procedure for Asymmetric Michael Reaction of 2-Hydroxy-2'-methoxyacetophenone (**3**) with Vinyl Ketones **2** and Indenones **5** Catalyzed by Et₂Zn/(*S,S*)-linked-BINOL **1** Complex (GP1):

To a stirred solution of (*S,S*)-linked-BINOL **1** (6.41 mg, 4.1w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) at –78 °C, was added Et₂Zn (20 μL, 0.02 mmol, 1.0 M in hexanes). After stirring for 30 min at –20 °C, a solution of 2-hydroxy-2'-methoxyacetophenone (**3**) (322.3 mg, 2.0 mmol) in THF (2.0 mL) was added. The resulting mixture was warmed to 4 °C, and *p*-methoxyphenyl vinyl ketone (**2a**) (1.0 mmol) was added and stirred at the same temperature. The stirring was continued for 8 h at this temperature and quenched by addition of saturated aqueous NH₄Cl (2 mL). The aqueous layer was separated and extracted with ethyl acetate (x 3) and the combined organic layers were washed with brine and dried over Na₂SO₄. The solvent was removed under reduced pressure and the resulting residue was purified by flash silica gel column chromatography (hexane/acetone 6/1) to afford **4a** (272.5 mg, 0.829 mmol, yield 83%).

Determination of Relative and Absolute Configuration.

The absolute configuration of **4c** was determined by Mosher's method. The absolute configuration of **4a-4b**, **4d-4f** was deduced from the result obtained from **4c**.

The relative configuration of **6a** was determined by X-ray crystallography of **6a** (ref. 15). The absolute configuration of **6a** was determined by Mosher's method. The relative and absolute configuration of **6b** and **6c** was deduced from the result obtained from **6a**.

(2*R*)-2-Hydroxy-1-(2-methoxyphenyl)-5-(4-methoxyphenyl)-1,5-pentanedione (**4a**):

colorless oil; IR (neat) ν 3460, 1671, 1599 cm⁻¹; ¹H NMR (CDCl₃) δ 1.72–1.79 (m, 1H), 2.25–2.32 (m, 1H), 2.98 (ddd, *J* = 5.0, 10.0, 17.0 Hz, 1H), 3.13 (ddd, *J* = 5.8, 9.8, 17.0 Hz, 1H), 3.84 (s, 3H), 3.89 (s, 3H), 3.93 (d, *J* = 5.5 Hz, 1H), 5.17 (ddd, *J* = 3.7, 5.5, 8.6 Hz, 1H), 6.87–6.92 (m, 2H), 6.96 (brd, *J* = 8.6 Hz, 1H) 7.02 (ddd, *J* = 1.0, 7.3, 8.0 Hz, 1H) 7.05 (ddd, *J* = 1.8, 7.3, 8.6 Hz, 1H), 7.81 (dd, *J* = 1.8, 8.0 Hz, 1H), 7.89–7.93 (m, 2H); ¹³C NMR (CDCl₃) δ 29.4, 34.0, 55.4, 55.6, 75.8, 111.7, 113.6, 121.0, 124.0, 130.0, 131.2, 134.5, 158.8, 163.4, 198.3, 202.9; EI-MS *m/z* 328 [M⁺], 135 [*o*-MeOC₆H₄CO⁺]; HRMS (FAB) [M+H]⁺ calcd for C₁₉H₂₁O₅, 329.1389; found, 329.1388; [α]_D²⁵ +98.5 (c

0.78 , CH₃Cl) (92% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) *t_R* 13.8 min (minor) and 18.5 min (major).

(2*R*)-2-Hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (4b):

colorless oil; IR (neat) 3467, 1683, 1598, 760 cm⁻¹; ¹H NMR (CDCl₃) δ 1.74-1.81 (m, 1H), 2.29-2.35 (m, 1H), 3.04 (ddd, *J* = 4.9, 9.8, 17.2 Hz, 1H), 3.19 (ddd, *J* = 5.8, 9.5, 17.2 Hz, 1H), 3.89 (s, 3H), 3.92 (d, *J* = 5.3 Hz, 1H), 5.19 (ddd, *J* = 3.7, 5.3, 8.3 Hz, 1H), 6.96 (brd, *J* = 8.3 Hz, 1H), 7.03 (ddd, *J* = 7.6, 7.6 Hz, 1H), 7.41-7.45 (m, 2H), 7.49-7.55 (m, 2H), 7.82 (dd, *J* = 1.8, 7.6 Hz, 1H), 7.92-7.94 (m, 2H); ¹³C NMR (CDCl₃) δ 28.9, 34.3, 55.6, 75.7, 111.7, 121.1, 124.0, 128.1, 128.6, 131.2, 133.0, 134.9, 136.8, 158.8, 199.7, 202.9; EI-MS *m/z* 298 [M⁺], 135 [*o*-MeOC₆H₄CO⁺], 105 [C₆H₅CO⁺]; HRMS calcd for C₁₈H₁₈O₄ 298.1205, found 298.1207; [α]_D²² +123.2 (*c* 0.24, CH₃Cl) (92% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) *t_R* 10.9 min (minor) and 13.6 min (major).

(2*R*)-2-Hydroxy-1,5-bis(2-methoxyphenyl)-1,5-pentanedione (4c):

colorless oil; IR (neat) 3470, 1670, 1598 cm⁻¹; ¹H NMR (CDCl₃) δ 1.70-1.76 (m, 1H), 2.24-2.29 (m, 1H), 3.07 (ddd, *J* = 5.2, 9.5, 17.7 Hz, 1H), 3.15 (ddd, *J* = 6.1, 9.5, 17.7 Hz, 1H), 3.86-3.87 (m, 4H), 3.90 (s, 3H), 5.17 (ddd, *J* = 3.7, 5.8, 9.5 Hz, 1H), 6.92 (brd, *J* = 8.3 Hz, 1H), 6.95 (ddd, *J* = 0.9, 7.3, 7.6 Hz, 1H), 6.96 (brd, *J* = 8.5 Hz, 1H), 7.03 (ddd, *J* = 0.9, 7.3, 7.6 Hz, 1H), 7.42 (ddd, *J* = 1.8, 7.3, 8.5 Hz, 1H), 7.50 (ddd, *J* = 1.8, 7.3, 8.3, 1H), 7.62 (dd, *J* = 1.8, 7.6 Hz, 1H), 7.80 (dd, *J* = 1.8, 7.6 Hz, 1H); ¹³C NMR (CDCl₃) δ 29.0, 39.5, 55.5, 55.6, 75.9, 111.5, 111.7, 120.5, 121.0, 124.2, 128.3, 130.2, 131.2, 133.3, 134.7, 158.5, 158.8, 202.0, 203.2; EI-MS *m/z* 328 [M⁺], 135 [*o*-MeOC₆H₄CO⁺]; HRMS (FAB) [M+H]⁺ calcd for C₁₉H₂₁O₅, 329.1389; found, 329.1392; [α]_D²⁴ +35.4 (*c* 0.32, CH₃Cl) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) *t_R* 12.3 min (minor) and 16.7 min (major).

(2*R*)-2-Hydroxy-5-(4-chlorophenyl)-1-(2-methoxyphenyl)-1,5-pentanedione (4d):

colorless oil; IR (neat) 1685, 1648, 1595 cm⁻¹; ¹H NMR (CDCl₃) δ 1.73-1.80 (m, 1H), 2.27-2.33 (m, 1H), 2.99 (ddd, *J* = 4.9, 9.1, 12.4 Hz, 1H), 3.15 (ddd, *J* = 6.1, 9.5, 12.4 Hz, 1H), 3.90 (s, 3H), 3.92 (d, *J* = 5.5 Hz, 1H), 5.17 (ddd, *J* = 3.6, 5.5, 9.1 Hz, 1H), 6.97 (brd, *J* = 8.2 Hz, 1H), 7.04 (ddd, *J* = 0.9, 7.6, 8.2 Hz, 1H), 7.39-7.41 (m, 2H), 7.52 (ddd, *J* = 1.8, 8.2, 8.2 Hz, 1H), 7.81 (dd, *J* = 1.8, 7.6 Hz, 1H), 7.85-7.88 (m, 2H); ¹³C NMR (CDCl₃) δ 28.8, 34.3, 55.7, 75.6, 111.8, 121.1, 123.9, 128.9, 129.5, 131.2, 135.0, 135.1, 139.5, 158.5, 198.5, 202.8; EI-MS *m/z* 332 [M⁺], 135 [*o*-MeOC₆H₄CO⁺]; HRMS calcd for C₁₈H₁₇ClO₄ 332.0815, found 332.0816; [α]_D²⁸ +113.2 (*c* 0.23, CH₃Cl) (92% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) *t_R* 10.9 min (minor) and 14.7 min (major).

(2*R*)-2-Hydroxy-1-(2-methoxyphenyl)-1,5-hexanedione (4e):

colorless oil; IR (neat) 3461, 1712, 1665, 760 cm⁻¹; ¹H NMR (CDCl₃) δ 1.55-1.63 (m, 1H), 2.07-2.17 (m, 1H), 2.11 (s, 3H), 2.48 (ddd, *J* = 5.2, 9.5, 17.7 Hz, 1H), 2.64 (ddd, *J* = 6.4, 9.2, 17.7 Hz, 1H), 3.84 (d, *J* = 5.8 Hz, 1H), 3.90 (s, 3H), 5.09 (ddd, *J* = 3.7, 5.8, 8.3 Hz, 1H), 6.96 (brd, *J* = 8.2 Hz, 1H), 7.03 (ddd, *J* = 0.9, 7.3, 7.6 Hz, 1H), 7.51 (ddd, *J* = 1.8, 7.3, 8.2 Hz, 1H), 7.79 (dd, *J* = 1.8, 7.6 Hz, 1H); ¹³C NMR (CDCl₃) δ 28.1, 30.2, 39.1, 55.6, 75.5, 111.7, 121.1, 124.0, 131.2, 134.9, 158.8, 202.8, 208.3; EI-MS *m/z* 236 [M⁺], 135 [*o*-MeOC₆H₄CO⁺]; HRMS calcd for C₁₃H₁₆O₄ 236.1049, found 236.1040; [α]_D²⁵ +96.2 (*c* 0.66, CH₃Cl) (93% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) *t_R* 8.0 min (minor) and 10.1 min (major).

(2*R*)-2-Hydroxy-1-(2-methoxyphenyl)-1,5-heptanedione (4f):

colorless oil; IR (neat) 3470, 1772, 1666, 1598, 760 cm⁻¹; ¹H NMR (CDCl₃) δ 1.00 (t, *J* = 7.4 Hz, 3H), 1.57-1.63 (m, 1H), 2.11-2.18 (m, 1H), 2.35-2.49 (m, 3H), 2.61 (ddd, *J* = 6.1, 9.2, 17.4 Hz, 1H), 3.83 (d, *J* = 5.5 Hz, 1H), 3.90 (s, 3H), 5.08 (ddd, *J* = 3.7, 5.5, 8.0 Hz, 1H), 6.96 (brd, *J* = 8.3 Hz, 1H), 7.02 (ddd, *J* = 0.6, 7.3, 7.6 Hz, 1H), 7.50 (ddd, *J* = 1.8, 7.3,

8.3 Hz, 1H), 7.79 (dd, $J = 1.8, 7.6$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 7.8, 28.2, 36.0, 37.7, 55.6, 75.5, 111.7, 121.0, 122.9, 131.6, 134.9, 138.8, 202.7, 211.0; EI-MS m/z 250 [M^+], 135 [$o\text{-MeOC}_6\text{H}_4\text{CO}^+$]; HRMS calcd for $\text{C}_{14}\text{H}_{18}\text{O}_4$ 250.1205, found 250.1201; $[\alpha]_{\text{D}}^{23} +88.3$ (c 1.1, CH_3Cl) (91% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 7.7 min (minor) and 10.1 min (major).

(3S)-3-[(R)-(o-Anisoyl)hydroxymethyl]-1-indanone (6a):

colorless solid; IR (KBr) 3456, 1670, 1597, 754 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.21 (dd, $J = 7.6, 18.6$ Hz, 1H), 2.50 (dd, $J = 3.4, 18.6$ Hz, 1H), 3.80 (ddd, $J = 2.1, 3.4, 7.6$ Hz, 1H), 3.94 (d, $J = 4.9$ Hz, 1H), 4.03 (s, 3H), 5.68 (dd, $J = 2.1, 4.9$ Hz, 1H), 7.03 (brd, $J = 8.1$ Hz, 1H), 7.06 (dd, $J = 8.0, 8.1$ Hz, 1H), 7.34-7.39 (m, 1H), 7.55 (ddd, $J = 1.9, 8.0, 8.1$ Hz, 1H), 7.62-7.70 (m, 3H), 7.84 (dd, $J = 1.9, 8.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 35.7, 41.1, 55.8, 77.5, 111.8, 121.6, 123.5, 123.8, 124.8, 128.0, 131.5, 134.8, 135.5, 137.6, 154.6, 158.7, 201.3, 205.1; EI-MS m/z 296 [M^+], 135 [$o\text{-MeOC}_6\text{H}_4\text{CO}^+$]; Anal calcd for $\text{C}_{18}\text{H}_{16}\text{O}_4$ C 72.96%, H 5.44%, found C 72.71%, H 5.51%; $[\alpha]_{\text{D}}^{23} -22.1$ (c 0.51, CH_3Cl) (99% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 16.2 min (minor) and 39.0 min (major).

(3S)-3-[(R)-(o-Anisoyl)hydroxymethyl]-5-bromo-1-indanone (6b):

colorless solid; IR (KBr) 3481, 1663, 1595 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.23 (dd, $J = 7.9, 18.6$ Hz, 1H), 2.36 (dd, $J = 3.7, 18.6$ Hz, 1H), 3.78-3.82 (m, 1H), 3.97 (d, $J = 4.9$ Hz, 1H), 4.06 (s, 3H), 5.63 (dd, $J = 2.2, 4.9$ Hz, 1H), 7.05 (brd, $J = 8.6$ Hz, 1H), 7.10 (ddd, $J = 0.7, 7.9, 8.1$ Hz, 1H), 7.51-7.61 (m, 3H), 7.78 (brs, 1H), 7.86 (dd, $J = 1.8, 7.9$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 35.7, 40.9, 55.9, 111.9, 121.6, 123.4, 128.3, 130.1, 131.5, 131.6, 135.6, 136.5, 156.6, 158.7, 200.8, 203.6; EI-MS m/z 374 [M^+], 135 [$o\text{-MeOC}_6\text{H}_4\text{CO}^+$]; HRMS calcd for $\text{C}_{18}\text{H}_{15}\text{BrO}_4$ 374.0154, found 374.0156; $[\alpha]_{\text{D}}^{27} -117.4$ (c 0.5, CH_3Cl) (99% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 17.1 min (minor) and 22.5 min (major).

(3S)-3-[(R)-(o-Anisoyl)hydroxymethyl]-6-methoxy-1-indanone (6c):

pale yellow solid; IR (KBr) 3451, 1652, 1598, 762 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.26 (dd, $J = 7.3, 16.6$ Hz, 1H), 2.37 (dd, $J = 3.3, 16.6$ Hz, 1H), 3.76 (ddd, $J = 2.2, 3.3, 7.3$ Hz, 1H), 3.81 (s, 3H), 3.92 (d, $J = 4.9$ Hz, 1H), 4.04 (s, 3H), 5.65 (dd, $J = 2.2, 4.9$ Hz, 1H), 7.04 (brd, $J = 8.3$ Hz, 1H), 7.08 (ddd, $J = 0.9, 7.3, 7.9$ Hz, 1H), 7.15 (d, $J = 2.5$ Hz, 1H), 7.25 (dd, $J = 2.5, 8.5$ Hz, 1H), 7.53 (d, $J = 8.5$ Hz, 1H), 7.57 (ddd, $J = 1.8, 7.3, 8.3$ Hz, 1H), 7.85 (dd, $J = 1.8, 7.9$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 36.3, 40.5, 55.6, 55.8, 77.5, 105.0, 111.8, 121.5, 123.6, 124.2, 125.5, 131.4, 135.4, 138.8, 147.7, 158.7, 159.9, 201.4, 205.4; EI-MS m/z 326 [M^+], 135 [$o\text{-MeOC}_6\text{H}_4\text{CO}^+$]; HRMS calcd for $\text{C}_{19}\text{H}_{18}\text{O}_5$ 326.1154, found 326.1145; $[\alpha]_{\text{D}}^{27} -6.3$ (c 0.97, CH_3Cl) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 22.7 min (minor) and 63.1 min (major).

(B) Second generation $\text{Et}_2\text{Zn}/(S,S)$ -linked-BINOL 1 = 4/1 System:

General Procedure for Asymmetric Michael Reaction of 2-Hydroxy-2'-methoxyacetophenone (3) with β -Substituted Enones 7 Catalyzed by $\text{Et}_2\text{Zn}/(S,S)$ -linked-BINOL 1 = 4/1 with MS 3A System (GP2):

MS3A (60 mg) in a test tube was dried at 160 $^{\circ}\text{C}$ under vacuum (0.7 KPa) for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (S,S) -linked-BINOL 1 (13.57 mg, 9.44 w/w% diethyl ether and hexane included, 0.02 mmol) in THF (0.3 mL) was charged. The resulting mixture was cooled to -20 $^{\circ}\text{C}$, and was added Et_2Zn (80 μL , 0.08 mmol, 1.0M in hexanes). After stirring for 30 min at this temperature, a solution of 3 (132.9 mg, 0.8 mmol) in THF (1.22 mL) and 7g (97.1 mg, 0.4 mmol) in THF (0.4 mL) was added successively. The stirring was continued for 5 h at this temperature and quenched with saturated aqueous NH_4Cl . The mixture was extracted with ethyl acetate and the combined organic layers were washed with brine and dried over Na_2SO_4 . The solvent was evaporated and the resulting residue was analyzed by ^1H NMR to determine diastereomeric ratio. The crude residue was purified by flash silica gel column chromatography (ethyl acetate/hexane = 1/10–1/5)

to afford **8g** (96% yield, *syn* = 95% ee, *anti* = 71% ee).

Determination of Relative and Absolute Configuration:

The relative configuration of major isomer of **8g** (*syn*-**8g**) was determined by X-ray crystallography of *syn*-**8g**. The relative configuration of Michael products obtained from acyclic enones, **8a**, **8b**, **8d-8f**, **8h-8n** was deduced from the result obtained from *syn*-**8g**. The relative configuration of major isomer of **8o** (*syn*-**8o**) was determined by X-ray crystallography. The relative configuration of Michael products obtained from cyclic enones, **8c**, **8p**, **8q** was deduced from the result obtained from *syn*-**8o**. The absolute configuration of *syn*-**8i** was determined by Mosher's method. The absolute configuration of Michael products obtained from acyclic enones, **8a**, **8b**, **8d-8h**, **8j-8n** was deduced from the result obtained from *syn*-**8i**. The absolute configuration of **8c**, **8o-8q** was deduced from the result obtained with **6a**.

(2*R*, 3*R*)-2-Hydroxy-1-(2-methoxyphenyl)-3,5-diphenyl-1,5-pentanedione (*syn*-**8a**):

colorless oil; IR (neat) ν 3455, 1684, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.42 (dd, J = 4.9, 15.9 Hz, 1H), 3.83-3.93 (m, 6H), 5.53 (dd, J = 2.1, 6.1 Hz, 1H), 6.95-6.98 (m, 2H), 7.01 (dd, J = 6.7, 8.0 Hz, 2H), 7.11-7.15 (m, 3H), 7.44-7.47 (m, 3H), 7.52-7.57 (m, 2H), 8.03 (dd, J = 1.2, 8.6 Hz, 2H); ^{13}C NMR (CDCl_3) δ 41.5, 43.8, 55.6, 78.4, 111.5, 120.8, 124.6, 127.0, 127.8, 128.1, 128.5, 128.7, 131.5, 133.0, 134.6, 137.2, 138.8, 158.7, 198.6, 201.4; ESI-MS m/z 397 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{24}\text{H}_{22}\text{O}_4\text{Cs}$ 507.0547 $[\text{M}+\text{Cs}]^+$, found 507.0552; $[\alpha]_{\text{D}}^{27}$ +116.0 (c 1.56, CHCl_3) (96% ee); HPLC (DAICEL CHIRALPAK AD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 8.2 min (minor) and 10.2 min (major).

(2*R*, 3*S*)-2-Hydroxy-1-(2-methoxyphenyl)-3,5-diphenyl-1,5-pentanedione (*anti*-**8a**):

colorless oil; IR (neat) ν 3460, 1685, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.12 (dd, J = 5.2, 17.4 Hz, 1H), 3.41 (dd, J = 8.9, 17.4 Hz, 1H), 3.79 (s, 3H), 3.86 (ddd, J = 2.5, 5.2, 8.6 Hz, 1H), 4.14 (d, J = 5.2 Hz, 1H), 5.39 (dd, J = 2.2, 5.2 Hz, 1H), 6.98 (d, J = 8.6 Hz, 1H), 7.07 (ddd, J = 0.9, 7.2, 7.2 Hz, 1H), 7.18-7.21 (m, 1H), 7.28 (dd, J = 8.0, 8.0 Hz, 2H), 7.36 (dd, J = 8.0, 8.0 Hz, 2H), 7.40-7.42 (m, 2H), 7.47-7.50 (m, 1H), 7.53-7.57 (m, 1H), 7.79 (dd, J = 1.2, 8.3 Hz, 2H), 7.78 (dd, J = 1.9, 7.7 Hz, 1H); ^{13}C NMR (CDCl_3) δ 38.5, 43.5, 55.4, 80.1, 111.6, 121.2, 124.1, 126.6, 128.0, 128.1, 128.3, 128.4, 131.6, 132.9, 135.0, 137.0, 143.5, 158.7, 198.1, 202.1; ESI-MS m/z 397 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{24}\text{H}_{22}\text{O}_4\text{Cs}$ 507.0547 $[\text{M}+\text{Cs}]^+$, found 507.0545; $[\alpha]_{\text{D}}^{26}$ +66.8 (c 0.56, CHCl_3) (93% ee); HPLC (DAICEL CHIRALPAK AD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 10.2 min (minor) and 15.6 min (major).

(2*R*, 3*R*)-2-Triethylsilyloxy-1-(2-methoxyphenyl)-3-phenyl-1,5-hexanedione (from *syn*-**8b**):

colorless oil; IR (neat) ν 1715, 1598 cm^{-1} ; ^1H NMR (C_6D_6) δ 0.72-0.86 (m, 6H), 1.12 (t, J = 7.9 Hz, 9H), 1.73 (s, 3H), 2.47 (dd, J = 5.2, 17.4 Hz, 1H), 3.12 (dd, J = 8.9, 17.4 Hz, 1H), 3.54 (s, 3H), 3.76 (ddd, J = 3.7, 5.2, 8.9 Hz, 1H), 5.90 (d, J = 3.7 Hz, 1H), 6.50 (d, J = 8.3 Hz, 1H), 6.66 (ddd, J = 0.9, 7.6, 7.6 Hz, 1H), 7.02-7.10 (m, 4H), 7.15-7.19 (m, 2H), 7.31 (dd, J = 1.5, 7.6 Hz, 1H); ^{13}C NMR (C_6D_6) δ 5.7, 7.3, 29.9, 44.0, 46.8, 55.3, 80.6, 111.2, 120.8, 127.0, 128.3, 128.4, 129.5, 131.5, 132.9, 140.9, 157.9, 201.2, 205.5; ESI-MS m/z 449 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{25}\text{H}_{35}\text{O}_4\text{Si}$ 427.2304 $[\text{M}+\text{H}]^+$, found 427.2309; $[\alpha]_{\text{D}}^{27}$ +29.0 (c 2.08, CH_2Cl_2) (90% ee); HPLC (DAICEL CHIRALPAK AD-H, 2-propanol/hexane 1/99, flow 0.8 mL/min, detection at 254 nm) t_{R} 11.0 min (major) and 12.7 min (minor).

(2*R*, 3*S*)-2-Triethylsilyloxy-1-(2-methoxyphenyl)-3-phenyl-1,5-hexanedione (from *anti*-**8b**):

white solid; IR (KBr) ν 1673, 1598 cm^{-1} ; ^1H NMR (C_6D_6) δ 0.59-0.73 (m, 6H), 1.00 (t, J = 8.0 Hz, 9H), 1.58 (s, 3H), 2.84 (dd, J = 8.3, 17.7 Hz, 1H), 2.99 (dd, J = 5.2, 17.7 Hz, 1H), 3.16 (s, 3H), 3.94 (ddd, J = 2.1, 5.2, 8.3 Hz, 1H), 5.57 (d, J = 2.2 Hz, 1H), 6.38 (d, J = 8.2 Hz, 1H), 6.75-6.78 (m, 1H), 7.02-7.19 (m, 4H), 7.36 (d, J = 7.8 Hz, 2H), 7.92 (dd, J = 1.9, 7.6 Hz, 1H); ^{13}C NMR (C_6D_6) δ 5.4, 7.1, 29.8, 42.4, 43.2,

54.9, 82.0, 111.6, 121.4, 126.8, 128.3, 128.3, 128.8, 131.6, 133.4, 143.9, 158.1, 201.1, 205.0; ESI-MS m/z 449 $[M+Na]^+$; HRMS (FAB) calcd for $C_{25}H_{35}O_4Si$ $[M+H]^+$ 427.2304, found 427.2305; $[\alpha]_D^{27}$ -1.8 (c 0.68, CH_2Cl_2) (9% ee); HPLC (DAICEL CHIRALPAK AD-H, 2-propanol/hexane 1/99, flow 0.8 mL/min, detection at 254 nm) t_R 17.4 min (minor) and 20.6 min (major).

(3R)-3-[(R)-(o-Anisoyl)triethylsilyloxymethyl]-cyclopentan-1-one (syn-8c):

colorless oil; IR (neat) ν 1742, 1686, 1598 cm^{-1} ; 1H NMR ($CDCl_3$) δ 0.57-0.69 (m, 6H), 0.94-0.97 (m, 9H), 1.87-2.12 (m, 4H), 2.23-2.36 (m, 2H), 2.50-2.58 (m, 1H), 3.90 (s, 3H), 5.32 (d, J = 2.5 Hz, 1H), 6.95 (d, J = 8.3 Hz, 1H), 6.99-7.02 (m, 1H), 7.45 (ddd, J = 1.8, 7.3, 8.2 Hz, 1H), 7.55 (dd, J = 1.8, 7.6 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 4.9, 6.8, 26.3, 37.9, 38.4, 39.7, 55.5, 78.6, 111.4, 121.2, 126.9, 130.3, 133.5, 157.6, 202.0, 218.7; ESI-MS m/z 385 $[M+Na]^+$; $[\alpha]_D^{26}$ +99.6 (c 2.43, $CHCl_3$) (85% ee); HPLC (DAICEL CHIRALPAK AS, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_R 18.9 min (major) and 31.0 min (minor); HRMS (FAB) $[M+H]^+$ calcd for $C_{20}H_{31}O_4Si$, 363.1986; found, 363.1987.

(2R,3R)-5-(4-Chlorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-3-phenyl-1,5-pentanedione (syn-8d):

colorless oil; IR (neat) ν 3456, 1685, 1598 cm^{-1} ; 1H NMR ($CDCl_3$) δ 3.36 (dd, J = 5.2, 16.2 Hz, 1H), 3.82 (dd, J = 7.9, 16.2 Hz, 1H), 3.87 (ddd, J = 2.5, 5.2, 8.0 Hz, 1H), 3.93 (s, 3H), 5.51 (d, J = 2.5 Hz, 1H), 6.93-6.94 (m, 2H), 6.97-7.02 (m, 2H), 7.10-7.16 (m, 3H), 7.41-7.43 (m, 3H), 7.53 (ddd, J = 1.8, 7.4, 8.5 Hz, 1H), 7.96 (d, J = 8.9 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 41.4, 43.7, 55.5, 78.3, 111.4, 120.8, 124.5, 127.0, 127.8, 128.6, 128.8, 129.5, 131.5, 134.6, 135.4, 138.5, 139.4, 158.6, 197.4, 201.2; ESI-MS m/z 431 $[M+Na]^+$; HRMS (FAB) calcd for $C_{24}H_{22}ClO_4$ 409.1201 $[M+H]^+$, found 409.1210; $[\alpha]_D^{26}$ +110.0 (c 2.13, $CHCl_3$) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_R 6.4 min (minor) and 7.7 min (major).

(2R,3S)-5-(4-Chlorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-3-phenyl-1,5-pentanedione (anti-8d):

colorless oil; IR (neat) ν 3458, 1686, 1598 cm^{-1} ; 1H NMR ($CDCl_3$) δ 3.09 (dd, J = 5.2, 17.4 Hz, 1H), 3.35 (dd, J = 8.6, 17.4 Hz, 1H), 3.79 (s, 3H), 3.83 (ddd, J = 2.1, 5.2, 8.6 Hz, 1H), 5.38 (d, J = 2.2 Hz, 1H), 6.98 (d, J = 8.5 Hz, 1H), 7.06-7.09 (m, 1H), 7.18-7.21 (m, 1H), 7.27-7.34 (m, 4H), 7.39 (brd, J = 7.1 Hz, 2H), 7.56 (ddd, J = 1.9, 7.4, 8.6 Hz, 1H), 7.70-7.73 (m, 2H), 7.88 (dd, J = 1.8, 7.9 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 38.5, 43.5, 55.4, 80.0, 111.6, 121.2, 126.7, 128.0, 128.4, 128.7, 129.4, 131.7, 135.1, 135.2, 139.4, 143.3, 158.7, 197.0, 202.0; ESI-MS m/z 431 $[M+Na]^+$; HRMS (FAB) calcd for $C_{24}H_{22}ClO_4$ 409.1201 $[M+H]^+$, found 409.1207; $[\alpha]_D^{26}$ +71.1 (c 0.45, $CHCl_3$) (83% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_R 9.6 min (minor) and 11.8 min (major).

(2R,3R)-5-(4-Fluorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-3-phenyl-1,5-pentanedione (syn-8e):

colorless oil; IR (neat) ν 3458, 1683, 1598 cm^{-1} ; 1H NMR ($CDCl_3$) δ 3.38 (dd, J = 5.2, 16.2 Hz, 1H), 3.80-3.89 (m, 3H), 3.94 (s, 3H), 5.51 (d, J = 2.5 Hz, 1H), 6.93-7.03 (m, 4H), 7.10-7.13 (m, 5H), 7.43 (dd, J = 1.5, 7.6 Hz, 1H), 7.52-7.56 (m, 1H), 8.04-8.07 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 41.4, 43.7, 55.5, 78.3, 111.5, 115.5, 115.7, 120.8, 127.0, 127.8, 128.6, 130.7, 130.8, 131.5, 134.7, 138.6, 158.6, 197.1, 201.3; ESI-MS m/z 415 $[M+Na]^+$; HRMS (FAB) calcd for $C_{24}H_{22}O_4F$ 393.1497 $[M+H]^+$, found 393.1497; $[\alpha]_D^{27}$ +109.5 (c 1.93, $CHCl_3$) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_R 6.3 min (minor) and 7.5 min (major).

(2R,3S)-5-(4-Fluorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-3-phenyl-1,5-pentanedione (anti-8e):

colorless oil; IR (neat) ν 3458, 1685, 1598 cm^{-1} ; 1H NMR ($CDCl_3$) δ 3.06 (dd, J = 5.2, 17.4 Hz, 1H), 3.34 (dd, J = 8.6, 17.4 Hz, 1H), 3.76 (s, 3H), 3.81 (ddd, J = 2.2, 5.2, 8.5 Hz, 1H), 5.36 (d, J = 2.2 Hz, 1H), 6.96 (d, J = 8.6 Hz, 1H), 7.00 (dd, J = 8.5, 8.5 Hz, 2H), 7.05 (dd, J = 7.7, 7.7 Hz, 1H),

7.17 (dd, $J = 7.4, 7.4$ Hz, 1H), 7.23-7.27 (m, 2H), 7.38 (d, $J = 7.4$ Hz, 2H), 7.51-7.55 (m, 1H), 7.77-7.80 (m, 2H), 7.86 (dd, $J = 1.6, 7.7$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 38.4, 43.5, 55.4, 80.1, 111.6, 115.4, 115.6, 121.2, 126.7, 128.0, 128.4, 130.5, 130.6, 131.7, 135.1, 143.4, 158.7, 196.6, 202.0; ESI-MS m/z 415 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{24}\text{H}_{21}\text{O}_4\text{FCs}$ 525.0472 $[\text{M}+\text{Cs}]^+$, found 525.0477; $[\alpha]_{\text{D}}^{27} +65.3$ (c 0.43, CHCl_3) (80% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 9.5 min (minor) and 11.6 min (major).

(2R,3R)-2-Hydroxy-1-(2-methoxyphenyl)-5-(4-methoxyphenyl)-3-phenyl-1,5- pentanedione (syn-8f):

colorless oil; IR (neat) ν 3459, 1671, 1600 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.35 (dd, $J = 5.8, 16.2$ Hz, 1H), 3.78-3.92 (m, 9H), 5.51 (d, $J = 2.5$ Hz, 1H), 6.92-7.02 (m, 6H), 7.10-7.16 (m, 3H), 7.45 (dd, $J = 1.8, 7.9$ Hz, 1H), 7.52-7.55 (m, 1H), 8.02 (d, $J = 8.9$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 41.1, 44.0, 55.4, 55.6, 78.4, 111.5, 113.7, 120.8, 124.6, 126.9, 127.7, 128.7, 130.3, 130.5, 131.5, 134.6, 138.8, 158.7, 163.5, 197.2, 201.5; ESI-MS m/z 427 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{25}\text{H}_{24}\text{O}_5\text{Cs}$ 537.0673 $[\text{M}+\text{Cs}]^+$, found 537.0685; $[\alpha]_{\text{D}}^{26} +120.5$ (c 0.31, CHCl_3) (97% ee); HPLC (DAICEL CHIRALCEL OD-H, 2-propanol/hexane 20/80, flow 0.5 mL/min, detection at 254 nm) t_{R} 16.5 min (minor) and 17.8 min (major).

(2R,3S)-2-Hydroxy-1-(2-methoxyphenyl)-5-(4-methoxyphenyl)-3-phenyl-1,5- pentanedione (anti-8f):

colorless oil; IR (neat) ν 3461, 1674, 1600 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.03 (dd, $J = 4.9, 17.4$ Hz, 1H), 3.38 (dd, $J = 8.5, 17.4$ Hz, 1H), 3.80-3.87 (m, 8H), 5.39 (d, $J = 2.2$ Hz, 1H), 6.83 (d, $J = 8.9$ Hz, 2H), 6.98 (d, $J = 8.3$ Hz, 1H), 7.07 (dd, $J = 7.3, 7.3$ Hz, 1H), 7.19 (dd, $J = 7.4, 7.4$ Hz, 1H), 7.26-7.29 (m, 2H), 7.41 (d, $J = 7.4$ Hz, 2H), 7.53-7.56 (m, 1H), 7.78 (d, $J = 8.9$ Hz, 2H), 7.87 (dd, $J = 1.9, 8.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 37.9, 43.5, 55.4, 55.4, 80.2, 111.6, 113.5, 121.2, 124.1, 126.6, 128.0, 128.3, 130.0, 130.2, 131.6, 135.0, 143.6, 158.7, 163.3, 196.6, 202.1; ESI-MS m/z 427 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{25}\text{H}_{25}\text{O}_5$ 405.1697 $[\text{M}+\text{H}]^+$, found 405.1686; $[\alpha]_{\text{D}}^{26} +49.5$ (c 0.13, CHCl_3) (50% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 13.0 min (minor) and 15.5 min (major).

(2R,3R)-3-(4-Chlorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5- pentanedione (syn-8g):

colorless solid; IR (KBr) ν 3426, 1685, 1657 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.42 (dd, $J = 6.4, 16.8$ Hz, 1H), 3.79 (dd, $J = 7.3, 17.1$ Hz, 1H), 3.88 (ddd, $J = 2.8, 6.7, 7.4$ Hz, 1H), 3.94 (s, 3H), 3.95 (d, $J = 5.8$ Hz, 1H), 5.49 (dd, $J = 2.8, 5.8$ Hz, 1H), 6.89 (d, $J = 8.3$ Hz, 2H), 6.99-7.03 (m, 2H), 7.09 (d, $J = 8.6$ Hz, 2H), 7.46 (dd, $J = 7.7, 8.0$ Hz, 3H), 7.53-7.57 (m, 2H), 8.01 (d, $J = 7.4$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 41.6, 43.1, 55.6, 78.4, 111.6, 120.9, 124.4, 127.9, 128.1, 128.6, 130.1, 131.5, 132.8, 133.2, 134.8, 137.0, 137.3, 158.7, 198.3, 201.2; ESI-MS m/z 431 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{24}\text{H}_{21}\text{ClO}_4\text{Cs}$ 541.0177 $[\text{M}+\text{Cs}]^+$, found 541.0178; $[\alpha]_{\text{D}}^{27} +174.0$ (c 1.43, CHCl_3) (95% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 0.8 mL/min, detection at 254 nm) t_{R} 8.6 min (minor) and 11.1 min (major).

(2R,3S)-3-(4-Chlorophenyl)-2-hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5- pentanedione (anti-8g):

pale yellow oil; IR (neat) ν 3458, 1685, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 3.06 (dd, $J = 4.9, 17.7$ Hz, 1H), 3.40 (dd, $J = 8.9, 17.7$ Hz, 1H), 3.81-3.85 (m, 4H), 5.34 (dd, $J = 2.1, 5.2$ Hz, 1H), 6.99 (d, $J = 8.6$ Hz, 1H), 7.06-7.09 (m, 1H), 7.24-7.26 (m, 2H), 7.36-7.38 (m, 4H), 7.48-7.51 (m, 1H), 7.56 (ddd, $J = 1.9, 7.4, 8.6$ Hz, 1H), 7.77-7.79 (m, 2H), 7.87 (dd, $J = 1.9, 7.7$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 38.3, 42.9, 55.5, 80.0, 111.7, 121.3, 123.9, 127.9, 128.4, 128.5, 129.5, 131.7, 132.4, 133.0, 135.2, 136.8, 142.0, 158.7, 197.8, 201.7; ESI-MS m/z 431 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{24}\text{H}_{22}\text{ClO}_4$ 409.1201 $[\text{M}+\text{H}]^+$, found 409.1196; $[\alpha]_{\text{D}}^{28} +53.9$ (c 0.50, CHCl_3) (79% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 0.8 mL/min, detection at 254 nm) t_{R} 11.3 min (minor) and 15.7 min (major).

(2R, 3R)-2-Hydroxy-1-(2-methoxyphenyl)-6-methyl-3-phenyl-1,5-heptanedione (syn-8h):

colorless oil; IR (neat) ν 3460, 1710, 1666, 1599 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.02 (d, $J = 7.1$ Hz, 3H), 1.10 (d, $J = 7.1$ Hz, 3H), 2.55-2.63 (m, 1H), 2.92 (dd, $J = 6.4$, 17.4 Hz, 1H), 3.28 (dd, $J = 7.7$, 17.4 Hz, 1H), 3.69 (ddd, $J = 2.7$, 6.5, 7.7 Hz, 1H), 3.87 (d, $J = 6.1$ Hz, 1H), 3.97 (s, 3H), 5.40 (dd, $J = 2.7$, 6.1 Hz, 1H), 6.86-6.88 (m, 2H), 6.97 (ddd, $J = 0.6$, 7.3, 7.6 Hz, 1H), 7.01 (d, $J = 8.2$ Hz, 1H), 7.07-7.13 (m, 3H), 7.37 (dd, $J = 1.6$, 7.7 Hz, 1H), 7.50-7.54 (m, 1H); ^{13}C NMR (CDCl_3) δ 17.9, 17.9, 41.4, 43.2, 43.4, 55.6, 78.3, 111.5, 120.7, 124.7, 126.9, 127.7, 128.6, 131.4, 134.5, 138.7, 158.6, 201.5, 212.9; ESI-MS m/z 363 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{21}\text{H}_{24}\text{O}_4$ 473.0724 $[\text{M}+\text{Cs}]^+$, found 473.0737; $[\alpha]_D^{29} +94.7$ (c 2.08, CHCl_3) (87% ee); HPLC (DAICEL CHIRALPAK AD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_R 5.3 min (minor) and 6.8 min (major).

(2R,3R)-2-Hydroxy-1-(2-methoxyphenyl)-6,6-dimethyl-3-phenyl-1,5-heptanedione (syn-8i):

colorless oil; IR (neat) ν 3460, 1703, 1667, 1599 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.09 (s, 9H), 2.97 (dd, $J = 6.7$, 17.7 Hz, 1H), 3.27 (dd, $J = 7.6$, 17.7 Hz, 1H), 3.69 (ddd, $J = 2.7$, 6.7, 7.6 Hz, 1H), 3.85 (brd, $J = 5.5$ Hz, 1H), 3.95 (s, 3H), 5.35-5.38 (m, 1H), 6.84-6.87 (m, 2H), 6.96 (ddd, $J = 0.9$, 8.3, 8.3 Hz, 1H), 7.00 (d, $J = 8.3$ Hz, 1H), 7.05-7.12 (m, 3H), 7.36 (dd, $J = 1.8$, 7.6 Hz, 1H), 7.51 (ddd, $J = 1.8$, 7.3, 8.8 Hz, 1H); ^{13}C NMR (CDCl_3) δ 26.1, 40.1, 43.1, 44.2, 55.6, 78.4, 111.5, 120.7, 124.7, 126.8, 127.7, 128.7, 131.4, 134.5, 138.8, 158.6, 201.7, 214.0; ESI-MS m/z 377 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{22}\text{H}_{27}\text{O}_4$ 355.1904 $[\text{M}+\text{H}]^+$, found 355.1907; $[\alpha]_D^{28} +77.0$ (c 2.0, CHCl_3) (74% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_R 10.4 min (minor) and 20.2 min (major).

(2R, 3S)-3-Ethyl-2-hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (syn-8j):

yellow oil; IR (neat) ν 3469, 1681, 1597 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.72 (t, $J = 7.6$ Hz, 3H), 1.10-1.18 (m, 1H), 1.21-1.30 (m, 1H), 2.49-2.54 (m, 1H), 2.96 (dd, $J = 4.9$, 16.5 Hz, 1H), 3.36 (dd, $J = 8.5$, 16.5 Hz, 1H), 3.82 (s, 3H), 3.88 (d, $J = 5.2$ Hz, 1H), 5.18 (dd, $J = 2.1$, 5.2 Hz, 1H), 6.96 (d, $J = 8.6$ Hz, 1H), 7.03 (brdd, $J = 7.6$, 7.6 Hz, 1H), 7.45-7.52 (m, 3H), 7.54-7.57 (m, 1H), 7.76 (dd, $J = 1.9$, 7.7 Hz, 1H), 8.05 (dd, $J = 1.6$, 8.6 Hz, 2H); ^{13}C NMR (CDCl_3) δ 11.9, 21.1, 39.6, 39.6, 55.4, 78.5, 111.6, 120.8, 124.6, 128.2, 128.5, 130.9, 133.0, 134.4, 137.5, 158.6, 200.1, 203.5; ESI-MS m/z 349 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{Cs}]^+$ calcd for $\text{C}_{20}\text{H}_{22}\text{O}_4$ 459.0572; found, 459.0554; $[\alpha]_D^{25} +22.7$ (c 1.90, CHCl_3) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 0.8 mL/min, detection at 254 nm) t_R 7.6 min (minor) and 9.4 min (major).

(2R, 3S)-2-Hydroxy-3-isobutyl-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (syn-8k):

pale yellow oil; IR (neat) ν 3471, 1677, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.40 (d, $J = 6.4$ Hz, 3H), 0.69 (ddd, $J = 3.1$, 10.1, 13.4 Hz, 1H), 0.75 (d, $J = 6.4$ Hz, 3H), 1.25 (ddd, $J = 4.0$, 10.7, 14.9 Hz, 1H), 1.32-1.40 (m, 1H), 2.58-2.64 (m, 1H), 2.83 (dd, $J = 3.7$, 16.5 Hz, 1H), 3.43 (dd, $J = 9.5$, 16.5 Hz, 1H), 3.83 (s, 3H), 5.18 (d, $J = 2.2$ Hz, 1H), 6.96 (d, $J = 8.3$ Hz, 1H), 7.03 (dd, $J = 7.5$, 7.5 Hz, 1H), 7.45-7.52 (m, 3H), 7.55-7.57 (m, 1H), 7.73 (dd, $J = 1.8$, 7.9 Hz, 1H), 8.04-8.06 (m, 2H); ^{13}C NMR (CDCl_3) δ 20.9, 23.8, 25.0, 35.7, 37.3, 39.9, 55.4, 78.3, 111.4, 120.6, 124.6, 128.2, 128.5, 130.9, 133.0, 134.4, 137.4, 158.5, 200.0, 203.7; ESI-MS m/z 377 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{22}\text{H}_{26}\text{O}_4$ 487.0880 $[\text{M}+\text{Cs}]^+$, found 487.0865; $[\alpha]_D^{26} +37.9$ (c 3.03, CHCl_3) (97% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_R 5.0 min (minor) and 5.9 min (major).

(2R, 3R)-2-Hydroxy-3-isobutyl-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (anti-8k):

colorless oil; IR (neat) ν 3468, 1684, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.90 (d, $J = 6.7$ Hz, 3H), 0.92 (d, $J = 6.8$ Hz, 3H), 1.21 (ddd, $J = 5.2$, 8.8, 13.7 Hz, 1H), 1.63 (ddd, $J = 4.9$, 8.9, 13.5 Hz, 1H), 1.72-1.80 (m, 1H), 2.58 (dd, $J = 4.0$, 17.1 Hz, 1H), 2.65-2.69 (m, 1H), 2.82 (dd, $J = 8.9$, 17.1 Hz, 1H), 3.86 (s, 3H), 5.29

(d, $J = 1.6$ Hz, 1H), 6.98 (d, $J = 8.3$ Hz, 1H), 7.02-7.05 (m, 1H), 7.36 (dd, $J = 7.7, 7.7$ Hz, 2H), 7.48-7.56 (m, 2H), 7.70 (dd, $J = 1.9, 7.6$ Hz, 1H), 7.73-7.75 (m, 2H); ^{13}C NMR (CDCl_3) δ 22.0, 23.4, 25.1, 34.9, 37.6, 41.7, 55.4, 78.0, 111.5, 121.1, 124.6, 127.9, 128.4, 131.0, 132.8, 134.7, 137.1, 158.3, 199.0, 204.1; ESI-MS m/z 377 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{22}\text{H}_{26}\text{O}_4\text{Cs}$ 487.0880 $[\text{M}+\text{Cs}]^+$, found 487.0877; $[\alpha]_{\text{D}}^{26} +63.8$ (c 0.58, CHCl_3) (65% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 1.0 mL/min, detection at 254 nm) t_{R} 6.2 min (minor) and 10.2 min (major).

(2*R*,3*R*)-3-*tert*-Butyldiphenylsilyloxymethyl-1-(2-methoxyphenyl)-5-phenyl-2-triethylsilyloxy-1,5-pentanedione (from *syn*-8l):

colorless oil; IR (neat) ν 1687, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.57-0.71 (m, 6H), 0.93-0.98 (m, 18H), 2.72 (dd, $J = 8.5, 17.3$ Hz, 1H), 2.76-2.84 (m, 1H), 2.98 (dd, $J = 3.4, 17.3$ Hz, 1H), 3.60-3.68 (m, 5H), 5.67 (d, $J = 1.8$ Hz, 1H), 6.88 (d, $J = 8.5$ Hz, 1H), 6.98 (dd, $J = 7.4, 7.4$ Hz, 1H), 7.25-7.37 (m, 8H), 7.40-7.47 (m, 3H), 7.52 (d, $J = 6.6$ Hz, 2H), 7.59 (d, $J = 6.4$ Hz, 2H), 7.76 (d, $J = 7.0$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 4.99, 6.93, 19.2, 26.8, 34.2, 40.0, 55.4, 64.2, 76.3, 111.3, 120.9, 127.6, 127.7, 128.0, 128.3, 129.5, 130.0, 132.7, 132.9, 133.4, 133.7, 135.5, 137.1, 157.4, 198.6, 204.3; ESI-MS m/z 703 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{41}\text{H}_{53}\text{O}_5\text{Si}_2$, 681.3431; found, 681.3446; $[\alpha]_{\text{D}}^{29} +30.8$ (c 0.87, CHCl_3) (81% ee). HPLC DAICEL (CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 5.69 min (minor) and 8.45 min (major).

(2*R*,3*S*)-3-*tert*-Butyldiphenylsilyloxymethyl-1-(2-methoxyphenyl)-5-phenyl-2-triethylsilyloxy-1,5-pentanedione (from *anti*-8l):

colorless oil; IR (neat) ν 1685, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.49-0.63 (m, 6H), 0.87 (t, $J = 8.0$ Hz, 9H), 0.94 (s, 9H), 2.76-2.83 (m, 1H), 3.09 (dd, $J = 8.3, 16.1$ Hz, 1H), 3.53 (dd, $J = 4.6, 16.1$ Hz, 1H), 3.57 (dd, $J = 5.5, 15.6$ Hz, 1H), 3.61 (dd, $J = 10.5, 15.6$ Hz, 1H), 3.70 (s, 3H), 5.46 (d, $J = 2.7$ Hz, 1H), 6.84 (d, $J = 8.0$ Hz, 1H), 6.92 (dd, $J = 7.6, 7.6$ Hz, 1H), 7.22-7.26 (m, 2H), 7.28-7.44 (m, 10H), 7.51-7.55 (m, 3H), 7.97 (d, $J = 7.4$ Hz, 2H); ^{13}C NMR (CDCl_3) δ 4.88, 6.84, 19.1, 26.8, 37.0, 41.3, 55.3, 62.5, 76.8, 111.2, 120.8, 127.3, 127.5, 127.6, 128.2, 128.5, 129.4, 129.5, 130.4, 132.8, 133.1, 133.4, 133.5, 135.4, 135.5, 137.1, 157.6, 199.5, 202.8; ESI-MS m/z 703 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{41}\text{H}_{53}\text{O}_5\text{Si}_2$, 681.3431; found, 681.3433; $[\alpha]_{\text{D}}^{29} -4.8$ (c 0.56, CHCl_3).

(2*R*,3*S*)-3-(2-Benzyloxymethoxy-ethyl)-2-hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (*syn*-8m):

colorless oil; IR (neat) ν 3466, 1680, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.37-1.44 (m, 1H), 1.48-1.55 (m, 1H), 2.74-2.81 (m, 1H), 3.05 (dd, $J = 4.9, 16.5$ Hz, 1H), 3.38-3.43 (m, 3H), 3.82 (s, 3H), 4.36 (d, $J = 11.5$ Hz, 1H), 4.41 (d, $J = 11.5$ Hz, 1H), 4.48 (s, 2H), 5.21 (d, $J = 8.2$ Hz, 1H), 7.02 (dd, $J = 7.3, 7.3$ Hz, 1H), 7.22-7.32 (m, 5H), 7.43-7.52 (m, 3H), 7.54-7.58 (m, 2H), 7.78 (dd, $J = 1.8, 7.6$ Hz, 1H), 8.03-8.05 (m, 2H); ^{13}C NMR (CDCl_3) δ 28.2, 35.2, 40.2, 55.5, 65.6, 69.1, 78.4, 94.1, 111.6, 120.8, 124.5, 127.6, 127.8, 128.2, 128.3, 128.6, 131.0, 133.0, 134.6, 137.3, 137.8, 158.7, 199.6, 203.2; ESI-MS m/z 485 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{28}\text{H}_{31}\text{O}_6$, 463.2120; found, 463.2119; $[\alpha]_{\text{D}}^{25} +20.7$ (c 0.57, CH_2Cl_2) (98% ee); HPLC (TES ether)(DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 19.9 min (major) and 37.9 min (minor).

(2*R*,3*R*)-3-(2-Benzyloxymethoxy-ethyl)-2-hydroxy-1-(2-methoxyphenyl)-5-phenyl-1,5-pentanedione (*anti*-8m):

colorless oil; IR (neat) ν 3463, 1683, 1598 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.96-2.06 (m, 1H), 2.15-2.23 (m, 1H), 2.77 (dd, $J = 4.3, 17.4$ Hz, 1H), 2.90 (dd, $J = 8.5, 17.4$ Hz, 1H), 3.02-3.05 (m, 1H), 3.12 (s, 3H), 3.68-3.78 (m, 2H), 4.21 (d, $J = 5.0$ Hz, 1H), 4.43 (d, $J = 6.3$ Hz, 1H), 4.45 (d,

$J = 6.3$ Hz, 1H), 4.57 (s, 2H), 5.38 (dd, $J = 1.5, 5.9$ Hz, 1H), 6.29 (d, $J = 8.3$ Hz, 1H), 6.65 (dd, $J = 7.6, 7.6$ Hz, 1H), 6.92-7.13 (m, 7H), 7.26 (d, $J = 7.6$ Hz, 2H), 7.66 (d, $J = 7.0$ Hz, 2H), 7.84 (dd, $J = 18, 7.9$ Hz, 1H); ^{13}C NMR (C_6D_6) δ 33.2, 35.0, 37.7, 54.9, 66.3, 69.2, 78.7, 94.6, 111.7, 121.1, 125.2, 127.6, 128.3, 128.5, 128.6, 131.4, 132.5, 134.3, 137.6, 138.8, 158.8, 198.1, 203.5; ESI-MS m/z 485 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{28}\text{H}_{31}\text{O}_6$, 463.2120; found, 463.2118; $[\alpha]_{\text{D}}^{25} +53.7$ (c 1.15, CH_2Cl_2) (69% ee); HPLC (TES ether)(DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 26.0 min (minor) and 31.6 min (major).

(2R,3S)-2-Triethylsilyloxy-1-(2-methoxyphenyl)-3-pentyl-1,5-hexanedione (syn-8n):

colorless oil; IR (neat) ν 3470, 1714, 1666, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.72 (t, $J = 7.3$ Hz, 3H), 0.83-1.01 (m, 4H), 1.02-1.11 (m, 4H), 2.18 (s, 3H), 2.26-2.32 (m, 1H), 2.45 (dd, $J = 4.6, 17.4$ Hz, 1H), 2.78 (dd, $J = 9.2, 17.4$ Hz, 1H), 3.78 (d, $J = 5.2$ Hz, 1H), 3.91 (s, 3H), 5.12 (dd, $J = 1.5, 5.2$ Hz, 1H), 6.97 (d, $J = 8.5$ Hz, 1H), 7.02 (dd, $J = 8.0, 8.0$ Hz, 1H), 7.49 (dd, $J = 8.0, 8.5$ Hz, 1H), 7.70 (brd, $J = 8.0$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 13.9, 22.2, 26.6, 27.7, 30.9, 31.5, 36.7, 44.9, 55.6, 78.3, 111.5, 120.8, 124.6, 130.9, 134.5, 158.6, 203.7, 208.7; ESI-MS m/z 329 $[\text{M}+\text{Na}]^+$; HRMS (FAB)(for benzoate) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{18}\text{H}_{27}\text{O}_4$, 411.2171; found, 411.2163; $[\alpha]_{\text{D}}^{27} +25.6$ (c 0.2, CHCl_3 , for TES ether) (93% ee); HPLC (for benzoate ester)(DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 25.6 min (major) and 31.1 min (minor).

(2R,3R)-2-Triethylsilyloxy-1-(2-methoxyphenyl)-3-pentyl-1,5-hexanedione (from anti-8n):

colorless oil; IR (neat) ν 1715, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.56-0.68 (m, 6H), 0.86 (t, $J = 7.4$ Hz, 1H), 0.96 (t, $J = 7.8$ Hz, 9H), 1.18-1.31 (m, 6H), 1.32-1.44 (m, 2H), 2.00 (s, 3H), 2.18-2.24 (m, 1H), 2.27 (dd, $J = 8.3, 17.7$ Hz, 1H), 2.37 (dd, $J = 3.6, 17.7$ Hz, 1H), 3.85 (s, 3H), 5.36 (d, $J = 1.8$ Hz, 1H), 6.91 (d, $J = 8.5$ Hz, 1H), 6.98 (dd, $J = 7.6, 7.6$ Hz, 1H), 7.42 (ddd, $J = 1.8, 7.6, 8.5$ Hz, 1H), 7.52 (dd, $J = 1.8, 7.6$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 4.9, 7.6, 14.1, 22.7, 27.0, 30.5, 31.8, 32.0, 36.8, 42.8, 55.3, 78.4, 111.2, 121.1, 127.0, 130.5, 133.4, 157.5, 203.6, 208.4; ESI-MS m/z 443 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{24}\text{H}_{41}\text{O}_4\text{Si}$, 421.2774; found, 421.2777; $[\alpha]_{\text{D}}^{27} +10.0$ (c 0.1, CHCl_3) (86% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 6.3 min (minor) and 7.1 min (major).

(3R)-3-[(R)-(o-Anisoyl)triethylsilyloxymethyl]-cyclohexan-1-one (syn-8o):

colorless solid; IR (neat) ν 1710, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.58-0.70 (m, 6H), 0.96-0.99 (m, 9H), 1.55-1.58 (m, 1H), 1.80 (ddd, $J = 3.4, 9.5, 9.5$ Hz, 2H), 1.97 (brd, $J = 12.8$ Hz, 1H), 2.03-2.16 (m, 2H), 2.20 (dd, $J = 6.1, 13.7$ Hz, 1H), 2.27 (brd, $J = 14.1$ Hz, 1H), 2.41 (dd, $J = 13.8, 13.8$ Hz, 1H), 3.87 (s, 3H), 5.26 (d, $J = 2.2$ Hz, 1H), 6.92 (d, $J = 8.2$ Hz, 1H), 6.98-7.06 (m, 1H), 7.42-7.45 (m, 1H), 7.58 (dd, $J = 1.5, 7.6$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 4.9, 6.8, 24.9, 29.1, 40.8, 40.9, 41.5, 55.5, 80.3, 111.4, 121.3, 126.7, 130.5, 133.5, 157.5, 201.4, 211.9; ESI-MS m/z 399 $[\text{M}+\text{Na}]^+$; $[\alpha]_{\text{D}}^{26} +46.1$ (c 2.67, CHCl_3) (99% ee); HPLC (DAICEL CHIRALPAK AS-H, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 15.8 min (major) and 19.8 min (minor); HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{21}\text{H}_{33}\text{O}_4\text{Si}$, 377.2143; found, 377.2153.

(3R)-3-[(R)-(o-Anisoyl)triethylsilylhydroxymethyl]cycloheptanone (from syn-8p):

colorless oil; IR (neat) ν 1699, 1598 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.55-0.64 (m, 6H), 0.94 (t, $J = 7.9$ Hz, 9H), 1.22-1.32 (m, 1H), 1.49-1.68 (m, 2H), 1.79-1.90 (m, 2H), 1.91-2.01 (m, 2H), 2.15-2.20 (m, 1H), 2.27 (ddd, $J = 4.0, 12.2, 16.2$ Hz, 1H), 2.35-2.42 (m, 1H), 2.54 (dd, $J = 11.5, 14.8$ Hz, 1H), 3.86 (s, 3H), 5.12 (d, $J = 1.2$ Hz, 1H), 6.91 (d, $J = 8.2$ Hz, 1H), 7.00 (dd, $J = 7.3, 7.6$ Hz, 1H), 7.43 (ddd, $J = 1.5, 7.3, 8.2$ Hz, 1H), 7.57 (dd, $J = 1.5, 7.6$ Hz, 1H); ^{13}C NMR (CDCl_3) δ 4.14, 6.08, 23.3, 27.9, 34.5, 38.7, 42.7, 43.0, 54.7, 81.3, 110.6, 120.5, 126.4, 129.7, 132.5, 156.7, 201.4, 213.3; ESI-

MS m/z 413 $[M+Na]^+$; HRMS (FAB) $[M+H]^+$ calcd for $C_{16}H_{21}O_4$, 277.1440; found, 277.1443; $[\alpha]_D^{30}$ +46.1 (c 0.8, $CHCl_3$) (98% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_R 21.2 min (minor) and 26.3 min (major).

(3R)-3-[(R)-(o-Anisoyl)hydroxymethyl]-N-benzylsuccinimide (syn-8q):

colorless solid; IR (KBr) ν 3376, 1708, 1669, 1597 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.31 (dd, J = 9.2, 18.0 Hz, 1H), 2.48 (dd, J = 4.6, 18.0 Hz, 1H), 3.27 (ddd, J = 1.6, 4.6, 9.2 Hz, 1H), 4.01 (s, 3H), 4.06 (d, J = 4.9 Hz, 1H), 4.67 (d, J = 14.4 Hz, 1H), 4.72 (d, J = 14.1 Hz, 1H), 5.76 (dd, J = 1.6, 4.9 Hz, 1H), 7.02 (d, J = 8.3 Hz, 1H), 7.07 (dd, J = 7.4, 7.4 Hz, 1H), 7.25-7.37 (m, 5H), 7.56-7.60 (m, 1H), 7.87 (dd, J = 1.5, 7.9 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 27.7, 42.6, 43.0, 55.7, 74.9, 112.0, 121.4, 122.7, 127.7, 128.4, 128.6, 131.5, 135.7, 135.8, 159.1, 175.9, 177.2, 200.0; ESI-MS m/z 376 $[M+Na]^+$; HRMS (FAB) calcd for $C_{20}H_{19}NO_5$ 376.1212 $[M+Cs]^+$, found 376.1214; $[\alpha]_D^{29}$ -40.8 (c 0.38, $CHCl_3$) (>99% ee); HPLC (DAICEL CHIRALCEL OD, 2-propanol/hexane 20/80, flow 0.8 mL/min, detection at 254 nm) t_R 7.6 min (minor) and 9.4 min (major).

Reaction Profiles of Michael Reaction of Methyl Vinyl Ketone 2e and 2-hydroxy-2'-methoxyacetophenone 3 with varied Zn/ligand ratio, and in the absence or presence of MS3A.

Procedure for the conditions (B): linked-BINOL 1 mol %, Et_2Zn 2 mol %

To a stirred solution of (*S,S*)-linked-BINOL **1** (6.79 mg, 9.4 w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) at $-20^\circ C$, was added Et_2Zn (20 mL, 0.02 mmol, 1.0 M in hexanes). After stirring for 30 min at the same temperature, a solution of ketone **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to $0^\circ C$, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at $0^\circ C$. Samples were taken at recorded times according to the following procedure: 0.1 mL of the reaction mixture was taken with a syringe filled with 0.3 mL of saturated aqueous NH_4Cl solution and was immediately poured onto saturated aqueous NH_4Cl (2.0 mL). The resulting mixture was extracted with ethyl acetate. After evaporating solvents, the crude residue was analyzed by 1H NMR. Yield of the product **4e** was measured by comparison of integrated area of methylene proton of **3** (2H, doublet, 4.77 ppm) and methylene proton of **4e** at C-3 position (1H, multiplet, 1.55-1.63 ppm and 1H, multiplet, 2.07-2.17 ppm, averaged value of them was employed). Numerical data for determining initial rate are summarized in the Table S(B)-1 below.

Table S(B)-1. Numerical Data for Plots in Figure 3.

time (min)	yield (%)			
	(A) Zn 2 mol %	(B) Zn 2 mol %, 1 1 mol %	(C) Zn 2 mol %, 1 0.5 mol %	(D) Zn 2 mol %, 1 0.5 mol %, with MS3A
5		5.6	4.6	15.1
10		10	8.2	27.8
15		13.6	12	34.7
20		17.4	15.2	35.6
25		20.1	18.2	48
30		23	22.1	53.4
40		29.9	21	66.1
50		33.5	31.8	73.8
60	19.3	38.3	39.3	77.3
80		47.3	48.1	79.5
100		53.1	52.3	85.7
120	31.2	58.5	62.7	87.1
150		63.5	64.1	84.3
180	34.2	68.2	71.9	88.2

Figure 3. Reaction profiles of 1,4-addition reaction using Et₂Zn alone, Et₂Zn/(*S,S*)-linked-BINOL **1** = 2/1, 4/1 without MS 3A and 4/1 with MS 3A systems.

General Procedure for Asymmetric Michael Reaction of 2-Hydroxy-2'-methoxyacetophenone (3**) with Enones **2e** Catalyzed by Et₂Zn/(*S,S*)-linked-BINOL **1** = 4/1 with MS 3A System (GP3):**

Procedure with 0.02 mol % ligand loading (substrate/ligand = 5000):

MS3A (2.0 g) in a flask was dried at 160 °C under vacuum (0.7 KPa) for 3h. After cooling down to room temperature, argon gas was refilled to the flask and a solution of (*S,S*)-linked-BINOL **1** (1.5 mg, 0.0025 mmol) in THF (1.0 mL) was charged. The resulting mixture was cooled to -20 °C, and was added Et₂Zn (10 μL, 0.01 mmol, 1.0 M in hexanes). After stirring for 10 min at -20 °C, and then a solution of ketone **3** (13.75 mmol) in THF (6.9 mL) was added. The mixture was warmed up to room temperature and **2e** (1.04 mL, 12.5 mmol) was added. The stirring was continued for 13 h at room temperature and quenched with aq. 1 M HCl. The mixture was extracted with ethyl acetate and the combined organic layers were washed with brine and dried over MgSO₄. The solvent was evaporated and the residue was purified by flash silica gel column chromatography (acetone/hexane = 1/10–1/5) to afford **4e** (2.66 g, 90% yield, 91% ee).

(C) Construction of Chiral Tetrasubstituted Carbon Stereocenter:

General Procedure for Asymmetric Michael Reaction of *rac*-2-Hydroxy-2'-methoxypropionophenone (*rac*-9**) with Vinyl Ketones (**2**) Catalyzed by Et₂Zn/(*S,S*)-linked-BINOL **1** = 4/1 with MS 3A (GP4):**

MS3A (30 mg) in a test tube was dried at 160 °C under vacuum (0.7 KPa) with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*S,S*)-linked-BINOL **1** (10.17 mg, 9.44 w/w% diethyl ether and hexane included, 0.015 mmol) in THF (0.4 mL)

was charged. The resulting mixture was cooled to $-20\text{ }^{\circ}\text{C}$, and was added Et_2Zn (60 μL , 0.06 mmol, 1.0 M in hexanes). After stirring for 20 min at this temperature, a solution of **9** (270.3 mg, 1.5 mmol) in THF (0.46 mL) and **2e** (25 μL , 0.3 mmol) was added successively. The stirring was continued for 16 h at this temperature and quenched with saturated aqueous NH_4Cl . The mixture was extracted with ethyl acetate and the combined organic layers were washed with brine and dried over Na_2SO_4 . The solvent was evaporated and the resulting crude residue was purified by flash silica gel column chromatography (acetone/hexane = 1/8) to afford **10e** (65.8 mg, 88% yield, 96% ee).

(2R)-2-Hydroxy-1-(2-methoxyphenyl)-5-(4-methoxyphenyl)-2-methyl-1,5-pentanedione (10a):

colorless oil; IR (neat) ν 3489, 1675, 1600 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.45 (s, 3H), 2.28 (ddd, J = 5.8, 9.8, 14.3 Hz, 1H), 2.55 (ddd, J = 5.2, 9.5, 14.3 Hz, 1H), 3.01 (ddd, J = 5.2, 9.8, 12.1 Hz, 1H), 3.09-3.17 (m, 1H), 3.13 (s, 3H), 3.22 (s, 1H), 4.31 (brs, 1H), 6.36 (d, J = 8.3 Hz, 1H), 6.62-6.65 (m, 2H), 6.72 (dd, J = 7.6, 7.6 Hz, 1H), 7.02 (ddd, J = 1.8, 7.6, 8.3 Hz, 1H), 7.23 (dd, J = 1.8, 7.6 Hz, 1H), 7.88-7.93 (m, 2H); ^{13}C NMR (C_6D_6) δ 25.6, 33.2, 34.2, 54.9, 55.1, 80.1, 111.3, 113.9, 121.0, 128.7, 129.9, 130.6, 130.6, 131.4, 156.3, 163.6, 198.0, 210.9; ESI-MS m/z 365 $[\text{M}+\text{Na}]^+$; HRMS (FAB) calcd for $\text{C}_{20}\text{H}_{23}\text{O}_5$ 343.1540 $[\text{M}+\text{H}]^+$, found 343.1535; $[\alpha]_{\text{D}}^{26}$ +6.2 (c 3.2, CHCl_3) (90% ee); HPLC (TMS ether) (DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 30.2 min (minor) and 36.4 min (major).

(2R)-2-Hydroxy-1-(2-methoxyphenyl)-2-methyl-5-phenyl-1,5-pentanedione (10b):

colorless oil; IR (neat) ν 3493, 1686, 1598, 1488 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.42 (s, 3H), 2.26 (ddd, J = 5.8, 9.8, 14.3 Hz, 1H), 2.52 (ddd, J = 5.0, 9.8, 14.3 Hz, 1H), 2.98 (ddd, J = 5.0, 9.8, 17.4 Hz, 1H), 3.06-3.13 (m, 1H), 3.08 (s, 3H), 4.15 (s, 1H), 6.33 (brd, J = 8.2 Hz, 1H), 6.70 (dd, J = 7.6, 7.6 Hz, 1H), 6.97-7.05 (m, 3H), 7.10-7.13 (m, 1H), 7.21 (dd, J = 1.5, 7.6 Hz, 1H), 7.84-7.86 (m, 2H); ^{13}C NMR (C_6D_6) δ 25.6, 33.4, 34.0, 55.1, 80.0, 111.4, 121.1, 128.3, 128.6, 128.7, 129.8, 131.3, 132.7, 137.5, 156.2, 199.2, 210.5; ESI-MS m/z 335 $[\text{M}+\text{Na}]^+$; $[\alpha]_{\text{D}}^{28}$ +2.9 (c 1.3, CH_2Cl_2) (93% ee); HPLC (TMS ether) (DAICEL CHIRALPAK AD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 16.6 min (minor) and 23.9 min (major); HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{19}\text{H}_{21}\text{O}_4$, 313.1434; found, 314.1426.

(2R)-2-Hydroxy-1,5-bis(2-methoxyphenyl)-2-methyl-1,5-pentanedione (10c):

colorless oil; IR (neat) ν 3491, 1674, 1598, 1486 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.46 (s, 3H), 2.32 (ddd, J = 5.8, 9.8, 15.1 Hz, 1H), 2.56 (ddd, J = 5.2, 9.5, 15.1 Hz, 1H), 3.14 (s, 3H), 3.17-3.35 (m, 2H), 3.23 (s, 3H), 4.17 (s, 1H), 6.39 (brd, J = 8.5 Hz, 1H), 6.44 (brd, J = 8.5 Hz, 1H), 6.72 (ddd, J = 0.9, 7.6, 7.6 Hz, 1H), 6.74 (ddd, J = 0.9, 7.6, 7.6 Hz, 1H), 7.03 (ddd, J = 0.9, 7.6, 8.5 Hz, 1H), 7.08 (ddd, J = 0.9, 7.6, 8.5 Hz, 1H), 7.24 (dd, J = 1.8, 7.6 Hz, 1H), 7.84 (dd, J = 1.8, 7.6 Hz, 1H); ^{13}C NMR (C_6D_6) δ 25.6, 34.4, 38.9, 55.0, 55.1, 80.1, 111.4, 111.8, 120.8, 121.0, 128.7, 129.1, 130.1, 130.7, 131.3, 133.2, 156.3, 158.3, 201.5, 211.0; ESI-MS m/z 365 $[\text{M}+\text{Na}]^+$; $[\alpha]_{\text{D}}^{28}$ +8.2 (c 1.8, CH_2Cl_2) (91% ee); HPLC (TMS ether) (DAICEL CHIRALCEL OD-H, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 19.9 min (major) and 22.5 min (minor); HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{20}\text{H}_{23}\text{O}_5$, 343.1540; found, 343.1545.

(2R)-2-Hydroxy-1-(2-methoxyphenyl)-2-methyl-1,5-hexanedione (10e):

colorless solid; IR (KBr) ν 3510, 1685, 1600 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.38 (s, 3H), 1.64 (s, 3H), 2.00-2.06 (m, 1H), 2.27-2.39 (m, 3H), 3.11 (s, 3H), 4.09 (s, 1H), 6.34 (brd, J = 7.7 Hz, 1H), 6.69-6.73 (m, 1H), 6.98-7.02 (m, 1H), 7.23 (dd, J = 1.5, 7.7, 1H); ^{13}C NMR (C_6D_6) δ 25.4, 29.3, 33.5, 38.0, 54.9, 79.8, 111.4, 121.2, 128.9, 129.9, 131.5, 156.2, 206.9, 210.6; ESI-MS m/z 273 $[\text{M}+\text{Na}]^+$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{14}\text{H}_{19}\text{O}_4$, 251.1283; found, 251.1275; $[\alpha]_{\text{D}}^{29}$ +1.1 (c 0.81, CHCl_3) (91% ee); HPLC (TMS ether) (DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 14.9 min (minor) and 17.6 min (major).

(2R)-2-Hydroxy-1-(2-methoxyphenyl)-2-methyl-1,5-heptanedione (10f):

colorless oil; IR (neat) ν 3491, 1704, 1599, 1488 cm^{-1} ; ^1H NMR (C_6D_6) δ 0.89 (t, $J = 7.3$ Hz, 3H), 1.39 (s, 3H), 2.03-2.10 (m, 1H), 2.27-2.41 (m, 3H), 3.11 (s, 3H), 4.05 (s, 1H), 6.33 (brd, $J = 8.2$ Hz, 1H), 6.71 (dd, $J = 7.3$, 7.6 Hz, 1H), 6.99 (ddd, $J = 1.8$, 7.6, 8.2 Hz, 1H), 7.24 (dd, $J = 1.8$, 7.3, 1H); ^{13}C NMR (C_6D_6) δ 7.92, 25.4, 33.5, 35.7, 36.7, 55.0, 79.8, 111.4, 121.1, 128.9, 129.9, 131.4, 156.2, 209.5, 210.6; ESI-MS m/z 287 $[\text{M}+\text{Na}]^+$; $[\alpha]_{\text{D}}^{29} +1.4$ (c 2.3, CH_2Cl_2) (91% ee); HPLC (TMS ether)(DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 13.0 min (minor) and 15.7 min (major); HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{15}\text{H}_{21}\text{O}_4$, 265.1434; found, 265.1440.

(2R)-2-Hydroxy-1-(2-methoxyphenyl)-2-methyl-5-(4-bromophenyl)-1,5-pentanedione (10g):

colorless oil; IR (neat) ν 3487, 1685, 1585, 1487 cm^{-1} ; ^1H NMR (C_6D_6) δ 1.41 (s, 3H), 2.21 (ddd, $J = 5.5$, 9.5, 15.1 Hz, 1H), 2.47 (ddd, $J = 5.5$, 9.8, 15.1 Hz, 1H), 2.83 (ddd, $J = 5.5$, 9.8, 17.4 Hz, 1H), 2.95 (ddd, $J = 5.5$, 9.5, 17.4 Hz, 1H), 3.07 (s, 3H), 4.11 (s, 1H), 6.32 (brd, $J = 8.3$ Hz, 1H), 6.71 (ddd, $J = 0.9$, 7.4, 7.4 Hz, 1H), 6.99 (ddd, $J = 1.8$, 7.4, 8.3 Hz, 1H), 7.13-7.17 (m, 2H), 7.21 (dd, $J = 1.8$, 7.4 Hz, 1H), 7.46-7.49 (m, 2H); ^{13}C NMR (C_6D_6) δ 25.6, 33.3, 33.9, 55.1, 79.9, 111.4, 121.1, 128.3, 128.8, 129.7, 129.8, 131.5, 131.9, 136.1, 156.2, 198.1, 210.3; ESI-MS m/z 413, 415 $[\text{M}+\text{Na}]^+$; $[\alpha]_{\text{D}}^{28} -3.4$ (c 0.82, CH_2Cl_2) (93% ee); HPLC (TMS ether)(DAICEL CHIRALCEL OD, 2-propanol/hexane 1/99, flow 1.0 mL/min, detection at 254 nm) t_{R} 18.8 min (minor) and 25.3 min (major); HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{19}\text{H}_{20}\text{O}_4\text{Br}$, 391.0540; found, 391.0537.

(D) Transformation of 1,4-adducts:

(2R)-2-Benzoyloxy-1,5-bis(2-methoxyphenyl)-1,5-pentanedione (11c)

To a stirred solution of **4c** (299.4 mg, 0.912 mmol, 90% ee) in pyridine (2.0 mL) were added DMAP (22 mg, 0.18 mmol) and benzoyl chloride (0.16 mL, 1.37 mmol) at 0 $^{\circ}\text{C}$. After being stirred for 2 h at room temperature, the reaction mixture was quenched with H_2O and extracted with ether (4 mL x 3). The combined organic extracts were washed successively with 1M HCl, saturated aqueous NaHCO_3 and brine and dried over Na_2SO_4 . The solvent was evaporated under reduced pressure and the resulting residue was purified by silica gel column chromatography (hexane/ethyl acetate 5/1) to give **11c** (347.4 mg, 0.803 mmol, yield 88%) as a colorless oil : IR (neat) ν 1720, 1679, 1598, 757 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.24-2.31 (m, 1H), 2.48-2.55 (m, 1H), 3.15-3.27 (m, 2H), 3.79 (s, 3H), 3.90 (s, 3H), 6.28 (dd, $J = 4.0$, 8.3 Hz, 1H), 6.90 (brd, $J = 8.3$ Hz, 1H), 6.93-6.97 (m, 2H), 7.02 (ddd, $J = 0.9$, 7.8, 7.8 Hz, 1H), 7.38-7.42 (m, 3H), 7.46-7.50 (m, 1H), 7.51-7.56 (m, 1H), 7.65 (dd, $J = 1.8$, 7.0 Hz, 1H), 7.82 (dd, $J = 1.8$, 7.8 Hz, 1H), 8.03-8.05 (m, 2H); ^{13}C NMR (CDCl_3) δ 25.3, 39.6, 55.4, 55.6, 78.6, 111.5, 111.5, 120.6, 120.9, 125.4, 128.0, 129.7, 129.9, 130.2, 131.2, 133.0, 133.5, 134.3, 158.5, 158.5, 166.1, 197.0, 201.2; EI-MS m/z 432 $[\text{M}^+]$; HRMS (FAB) $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{26}\text{H}_{25}\text{O}_6$, 433.1651; found, 433.1646; $[\alpha]_{\text{D}}^{26} -23.5$ (c 2.7, CHCl_3).

(2R)-2-Benzoyloxy-*N,N'*-bis(2-methoxyphenyl)pentanediamide (12c):

To a stirred solution of **11c** (100.9 mg, 0.233 mmol) in CH_2Cl_2 (2.0 mL) at room temperature was added *O*-mesitylenesulfonylhydroxylamine (MSH, prepared by the procedure of a literature cited in ref 20) (200.6 mg, 0.932 mmol) at room temperature. After stirring for 24 h at the same temperature, the reaction mixture was concentrated under reduced pressure and the resulting residue was purified by silica gel column chromatography (hexane/ethyl acetate 3/1) to give **12c** (86.3 mg, 0.187 mmol, yield 80%) as a colorless foam : IR (neat) ν 1727, 1685, 1601 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.48-2.68 (m, 4H), 3.71 (s, 3H), 3.77 (s, 3H), 5.67 (dd, $J = 4.6$, 6.5 Hz, 1H), 6.79 (dd, $J = 1.2$, 8.0 Hz, 1H), 6.83 (dd, $J = 1.2$, 8.0 Hz, 1H), 6.90 (ddd, $J = 1.2$, 8.0, 8.0 Hz, 1H), 6.93-7.01 (m, 2H), 7.05 (ddd, $J = 1.8$, 8.0, 8.0 Hz, 1H), 7.39-7.43 (m, 2H), 7.55-7.59 (m, 1H), 7.84 (brs, 1H), 8.07-8.10 (m, 2H), 8.27 (dd, $J = 1.8$, 8.0 Hz, 1H), 8.36 (dd, $J = 1.8$, 8.0 Hz, 1H), 8.75 (brs, 1H); ^{13}C NMR (CDCl_3) δ 27.8, 33.3, 55.5, 55.6, 73.1, 109.7,

109.9, 119.7, 119.8, 120.9, 121.1, 123.6, 124.3, 126.7, 127.5, 128.5, 129.0, 130.0, 133.7, 147.7, 148.0, 165.0, 167.1, 169.6; EI-MS m/z 462 [M^+], 105 [$PhCO^+$]; HRMS calcd for $C_{26}H_{26}N_2O_6$ 462.1791, found 462.1788; $[\alpha]_D^{24}$ -52.8 (c 0.61, $CHCl_3$).

(2R)-2-Benzoyloxy-N,N'-bis(2-methoxyphenyl)-1,5-pentanediamine (13c):

To a stirred solution of **12c** (42.9 mg, 0.0928 mmol) in CH_2Cl_2 (1.0 mL) at $-78^\circ C$ was added diisobutylaluminum hydride (DIBAL, 0.54 mL, 0.557 mmol, 1.04 M in toluene). The reaction mixture was allowed to warm to room temperature and stirred for 2 h at room temperature and then quenched with saturated aqueous NH_4Cl solution (2mL), followed by addition of potassium sodium (+)-tartrate tetrahydrate (Rochelle salt, 100mg). After stirring for 2h at room temperature, the resulting mixture was extracted with CH_2Cl_2 (2 mL x 3) and the combined organic extracts were washed with brine and dried over Na_2SO_4 . The solvent was evaporated under reduced pressure and the resulting residue was purified by flash silica gel column chromatography (hexane/ethyl acetate 3/1) to afford **13c** (24.7 mg, 0.074 mmol, yield 81%) as a colorless oil: IR (neat) ν 3417, 737 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.59-1.91 (m, 5H), 3.06 (dd, J = 8.1, 12.8 Hz, 1H), 3.18 (dd, J = 7.0, 7.0 Hz, 2H), 3.25 (dd, J = 3.4, 12.8 Hz, 1H), 3.80-3.91 (m, 9H), 6.08-6.71 (m, 4H), 6.74-6.78 (m, 2H), 6.83-6.87 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 25.9, 32.6, 43.8, 50.3, 55.4, 70.1, 109.4, 109.5, 110.0, 110.3, 116.5, 117.1, 121.2, 121.3, 138.1, 138.2, 146.9, 147.1; EI-MS m/z 330 [M^+]; HRMS calcd for $C_{19}H_{26}N_2O_3$ 330.1943, found 330.1937; $[\alpha]_D^{25}$ -4.6 (c 0.60, $CHCl_3$).

Bis(2-methoxyphenyl) (2R)-2-Benzoyloxypentanedioate (14c):

To a stirred solution of **11c** (59.7 mg, 0.138 mmol) in dichloroethane (2.0 mL) at room temperature were added anhydrous NaH_2PO_4 (165.6 mg, 1.38 mmol) and *m*-chloroperoxybenzoic acid (190.6 mg, 1.104 mmol). After being stirred for 24 h at $50^\circ C$, the reaction mixture was quenched with saturated aqueous $Na_2S_2O_3$. The resulting mixture was extracted with ethyl acetate (2 mL x 3). The combined organic extracts were washed with ice-cooled saturated aqueous $NaHCO_3$ (2 mL x 2) and brine, and then dried over Na_2SO_4 . The solvent was evaporated under reduced pressure, and the residue was purified by flash silica gel column chromatography (hexane/ethyl acetate 5/1) to give **14c** (43.6 mg, 0.0938 mmol, yield 68%) as a colorless oil : IR (neat) ν 1765, 1726, 751 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.52-2.67 (m, 2H), 2.91-2.95 (m, 2H), 3.74 (s, 3H), 3.77 (s, 3H), 5.60 (dd, J = 5.1, 7.0 Hz, 1H), 6.86-6.91 (m, 4H), 6.96 (dd, J = 1.5, 7.9 Hz, 1H), 7.04 (dd, J = 1.5, 7.9 Hz, 1H), 7.12-7.16 (m, 2H), 7.32-7.42 (m, 2H), 7.50-7.54 (m, 1H), 8.04-8.08 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 26.8, 29.5, 55.7, 71.5, 112.3, 120.7, 120.8, 122.7, 122.8, 126.9, 127.2, 128.4, 129.2, 129.9, 133.4, 139.1, 139.5, 150.8, 165.8, 167.8, 170.6; EI-MS m/z 464 [M^+]; HRMS (FAB) [$M+H$] $^+$ calcd for $C_{26}H_{25}O_8$, 465.1549; found, 465.1552; $[\alpha]_D^{22}$ +18.3 (c 0.65, $CHCl_3$).

(4S)-4-[(R)-(o-Anisoyl)hydroxymethyl]-2-oxo-1,2,3,4-tetrahydroquinoline (16a):

To a stirred solution of **6a** (48.3 mg, 0.163 mmol, 99% ee) in CH_3CN (1.0 mL), was added MSH (105.3 mg, 0.489 mmol) at room temperature. After stirring for 24 h at the same temperature, the reaction mixture was concentrated under reduced pressure and the resulting residue was purified by silica gel column chromatography (hexane/ethyl acetate 3/1) to give **15a** (73.7 mg, 0.149 mmol, yield 92%) as a colorless foam (15/1 diastereomixture based on 1H NMR). To a stirred solution of **15a** (43.6 mg, 0.0883 mmol) in CH_2Cl_2 (2.0 mL) was added $AlCl_3$ (0.132 mmol) at room temperature. After stirring for 30 min at the same temperature, the reaction mixture was quenched by addition of saturated aqueous $NaHCO_3$ (2.0 mL) and H_2O (2.0 mL) and water layer was saturated with potassium sodium (+)-tartrate tetrahydrate (Rochelle salt). After stirring for 30 min at room temperature, the reaction mixture was extracted with CH_2Cl_2 (2.0 mL x 4) and combined organic extracts were washed with brine and dried over Na_2SO_4 . The solvent was evaporated under reduced pressure, and the residue was purified by flash silica gel column chromatography (hexane/ethyl acetate 1/1) to give **16a** (22.6 mg, 0.0726 mmol, yield 82%) as a colorless solid : IR (KBr) ν 1678, 1596, 755 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.32 (dd, J = 7.0, 16.5 Hz, 1H), 2.45 (dd, J = 6.4, 16.5 Hz, 1H), 3.42 (ddd, J = 2.5, 6.4, 7.0 Hz, 1H), 3.93 (s, 3H), 4.08 (d, J = 5.2 Hz, 1H), 5.90 (dd, J = 2.5, 5.2 Hz, 1H), 6.74 (dd J = 1.2, 7.6 Hz, 1H), 6.97 (brd, J = 8.6 Hz, 1H), 7.01

(ddd, $J = 1.2, 7.9, 7.9$ Hz, 1H), 7.07 (ddd, $J = 1.0, 7.3, 7.6$ Hz, 1H), 7.17 (ddd, $J = 1.3, 7.6, 7.9$ Hz, 1H), 7.29 (brd, $J = 7.9$ Hz, 1H), 7.54 (ddd, $J = 1.8, 7.3, 8.6$ Hz, 1H), 7.85 (dd, $J = 1.8, 7.6$ Hz, 1H), 8.11 (brs, 1H); ^{13}C NMR (CDCl_3) δ 30.5, 39.4, 55.7, 79.1, 111.7, 115.8, 121.5, 123.6, 123.8, 127.1, 128.1, 131.5, 135.3, 137.8, 158.6, 170.7, 201.4; EI-MS m/z 311 [M^+], 135 [$o\text{-MeOC}_6\text{H}_4\text{CO}^+$]; HRMS calcd for $\text{C}_{18}\text{H}_{17}\text{NO}_4$ 311.1158, found 311.1158; $[\alpha]_{\text{D}}^{25} -66.0$ (c 0.35, CHCl_3).

(E) Mechanistic Studies and Discussion:

(E-1) Reaction Profiles of 1,4-Addition Reaction with Optically Active Ketone (*S*)-**9** (99% ee) Catalyzed by (a) $\text{Et}_2\text{Zn}/(R,R)\text{-linked-BINOL}$ and (b) $\text{Et}_2\text{Zn}/(S,S)\text{-linked-BINOL}$.

Optically active ketone **9** was obtained by the following procedure.

MS3A (400 mg) in a test tube was dried at 160 °C under vacuum with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*R,R*)-linked-BINOL **1** (136.4 mg, 9.1 w/w% diethyl ether and hexane included, 0.2 mmol) in THF (3.0 mL) was charged. The resulting mixture was cooled to -20 °C, and was added Et_2Zn (60 μL , 0.06 mmol, 1.0M in hexanes). After stirring for 20 min at this temperature, a solution of racemic **9** (1500 mg, 8.3 mmol) in THF (2.54 mL) and hydrocinnamaldehyde (526.7 μL , 4 mmol) was added successively. The stirring was continued for 24 h at this temperature and quenched with saturated aqueous NH_4Cl . The mixture was extracted with ethyl acetate and the combined organic layers were washed with brine and dried over Na_2SO_4 . Evaporation of solvent gave a crude mixture and the remaining ketone **9** was isolated by flash silica gel column chromatography (acetone/hexane = 1/8) and successively conducted for asymmetric aldol reaction just described above. After repeating asymmetric aldol reaction for four times, optically pure **9** (572 mg, 99.3% ee, HPLC analysis: DAICEL CHIRALCEL OD, 2-isopropanol/hexane = 1/9, flow 1.0 mL/min, detection at 254 nm, t_{R} 7.4 min (major) and 10.2 min (minor)) was obtained.

Procedure for Michael reaction with optically active (*S*)-**9** using (*S,S*)-linked-BINOL **1**:

MS3A (30 mg) in a test tube was dried at 160 °C under vacuum (0.7 KPa) with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*S,S*)-linked-BINOL **1** (10.17 mg, 9.44 w/w% diethyl ether and hexane included, 0.015 mmol) in THF (0.4 mL)

<reaction profile>

was charged. The resulting mixture was cooled to -20 °C, and was added Et_2Zn (60 μL , 0.06 mmol, 1.0M in hexanes). After stirring for 20 min at this temperature, a solution of (*S*)-**9** (135.2 mg, 0.75 mmol, 99.3%

ee) in THF (0.46 mL) and **2e** (25 μ L, 0.3 mmol) was added successively. Samples were taken at recorded times according to the following procedure: 0.05 mL of the reaction mixture was taken with a syringe filled with 0.1 mL of saturated aqueous NH_4Cl solution and was immediately poured onto saturated aqueous NH_4Cl (1.0 mL). The resulting mixture was extracted with ether. After evaporating solvents, the crude residue was analyzed by ^1H NMR (C_6D_6). Yields of the products **10e** were measured by comparison of integrated area of methyl proton at C-2 position of **10e** (singlet, 1.38 ppm) and methyl proton at C-2 position of the **9** (doublet, 1.29 ppm).

Figure 5. Reaction profiles of 1,4-addition reaction with optically active ketone (*S*)-**9** (99% ee) catalyzed by (a) $\text{Et}_2\text{Zn}/(R,R)$ -linked-BINOL and (b) $\text{Et}_2\text{Zn}/(S,S)$ -linked-BINOL.

Numerical data are summarized in TableS(E)-1.

Table S(E)-1. Numerical Data for Plots in Figure 5.

2e

+

S-9
2.5 eq.
(99.3% ee)

(a): (*S,S*)-linked-BINOL 5 mol %
or
(b): (*R,R*)-linked-BINOL 5 mol %

Et₂Zn 20 mol %
THF, -20 °C

→

10e

(a): (*S,S*)-linked-BINOL (5 mol %), Et₂Zn (20 mol %)

time (h)	1	6	12	20	30	48	72
yield (%)	1.46	19.67	29.32	39.56	45.04	53.24	59.1

(b): (*R,R*)-linked-BINOL (5 mol %), Et₂Zn (20 mol %)

time (h)	1	6	12	20	30	48	72
yield (%)	0.63	0.78	1.15	1.13	1.13	1.09	1.27

(E-2) Kinetic Study of Michael Addition of Methyl Vinyl Ketone (2e**) and 2-hydroxy-2'-methoxyacetophenone (**3**) with Varied Amount of Catalyst, **2e** and **3** in the Absence or Presence of MS3A.**

(E-2)-1: Initial rate kinetics on catalyst concentration.

Procedure for the reaction with 1 mol % of linked-BINOL **1 and 2 mol % of Et_2Zn .**

To a stirred solution of (*S,S*)-linked-BINOL **1** (6.79 mg, 9.4w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) at -20°C , was added Et_2Zn (20 μL , 0.02 mmol, 1.0 M in hexanes). After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to 0°C , and **2e** (1.0 mmol) was added. The reaction mixture was stirred at 0°C . Samples were taken at recorded times according to the following procedure: 0.1 mL of the reaction mixture was taken with a syringe filled with 0.3 mL of saturated aqueous NH_4Cl solution and was immediately poured onto saturated aqueous NH_4Cl (2.0 mL). The resulting mixture was extracted with ethyl acetate. After evaporating solvents, the crude residue was analyzed by ^1H NMR. Yield of the product **4e** was measured by comparison of integrated area of methylene proton of **3** (2H, doublet, 4.77 ppm) and methylene proton of **4e** at C-3 position (1H, multiplet, 1.55-1.63 ppm and 1H, multiplet, 2.07-2.17 ppm, averaged value of them was employed). Numerical data for determining initial rate are summarized in each section.

Figure S(E)-1. Initial rate kinetics on catalyst concentration.

Table S(E)-2. Numerical Data for Plots in Figure S(E)-1.

time (min)	yield(%)		
	x=0.5	x=1	x=3
5		3.5	8.7
10		5.3	14.6
15	5.4	9.3	20
20	7.3	11.4	25.7
25	8.7	14.5	29.7
30	10.4	17	34.3

0.7-order rate dependency was observed on catalyst concentration.

(E-2)-2: Initial rate kinetics on ketone **3 concentration.**

Procedure for the Michael reaction with 0.8 M ketone **3 concentration.**

To a stirred solution of (*S,S*)-linked-BINOL **1** (6.79 mg, 9.4w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) at $-20\text{ }^\circ\text{C}$, was added Et_2Zn (20 μL , 0.02 mmol, 1.0 M in hexanes). After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to $0\text{ }^\circ\text{C}$, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at $0\text{ }^\circ\text{C}$. Sampling and determination of chemical yields were carried out by the same procedure as described in section (E-2)-1.

Figure S(E)-2. Initial rate kinetics on ketone **3** concentration.

Numerical data are summarized in Table S(E)-3.

0.8-order rate dependency was observed on ketone **3** concentration.

(E-2)-3: Initial rate kinetics on enone **2e concentration.**

Procedure for the Michael reaction with 0.4 M enone **2e concentration.**

Table S(E)-3. Numerical Data for Plots in Figure S(E)-2.

time (min)	yield (%)		
	ketone 3 0.2M	ketone 3 0.4M	ketone 3 0.8M
5	5.6	8.74	17.7
10	11.1	15.9	29.4
15			39.4
20	18.8	29.9	54.3
25			68
30		43.8	
40	37.9	56.9	
60	52.8		

To a stirred solution of (*S,S*)-linked-BINOL **1** (6.79 mg, 9.4w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) at $-20\text{ }^{\circ}\text{C}$, was added Et_2Zn (20 μL , 0.02 mmol, 1.0 M in hexanes). After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to $0\text{ }^{\circ}\text{C}$, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at $0\text{ }^{\circ}\text{C}$. Sampling and determination of chemical yields were carried out by the same procedure as described in section (E-2)-1.

Figure S(E)-3. Initial rate kinetics on enone **2e** concentration.

Table S(E)-4. Numerical Data for Plots in Figure S(E)-3.

time (min)	yield (%)		
	2e 0.12M	2e 0.2M	2e 0.4M
5			15.7
10	10.7	12.8	29.8
15	14.6	24	45.4
20	20.6	30.2	59.6
25	24.7	37.3	67.8
30	28.8	44.6	76.4
40	38.5	56.7	97.7

0.8-order rate dependency was observed on enone **2e** concentration.

(E-2)-4: Initial rate kinetics on catalyst concentration in the presence of MS 3A.

Procedure for the Michael reaction with 1 mol % of linked-BINOL **1 and 2 mol % of Et_2Zn .**

MS3A (75 mg) in a test tube was dried at $160\text{ }^{\circ}\text{C}$ under vacuum (0.7 KPa) with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*S,S*)-linked-BINOL **1** (6.79 mg, 9.4w/w% diethyl ether and hexane included, 0.01 mmol) in THF (0.3 mL) was charged. The resulting mixture was cooled to $-20\text{ }^{\circ}\text{C}$, and Et_2Zn (20 μL , 0.02 mmol, 1.0 M in hexanes) was added. After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to $0\text{ }^{\circ}\text{C}$, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at $0\text{ }^{\circ}\text{C}$. Sampling and determination of chemical yields were carried out by the same procedure as described in section (E-2)-1.

First-order rate dependency was observed on catalyst concentration.

(E-2)-5: Initial rate kinetics on ketone **3 concentration in the presence of MS 3A.**

Procedure for the Michael reaction with 0.8 M ketone **3 concentration in the existence of MS 3A.**

MS3A (75 mg) in a test tube was dried at 160 °C under vacuum (0.7 KPa) with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*S,S*)-linked-BINOL **1** (3.39 mg, 9.4w/w% diethyl ether and hexane included, 0.005 mmol) in THF (0.3 mL) was charged. The resulting mixture was cooled to –20 °C, and Et₂Zn (20 µL, 0.02 mmol, 1.0 M in hexanes) was added. After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to 0 °C, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at 0 °C. Sampling and determination of chemical yields were

Figure S(E)-4. Initial rate kinetics on catalyst concentration with MS3A.

carried out by the same procedure as described in section (E-2)-1.

Table S(E)-5. Numerical Data for Plots in Figure S(E)-4.

time (min)	yield (%)			
	<i>x</i> =0.1	<i>x</i> =0.25	<i>x</i> =0.5	<i>x</i> =1.0
5	6	11.3	22.7	34.6
10	11.6	20	40	63.7
15	16.8	30.4	57	79.9

Figure S(E)-5. Initial rate kinetics on ketone **3** concentration with MS3A.

Table S(E)-6. Numerical Data for Plots in Figure S(E)-5.

time[min]	yield (%)			
	ketone 3 0.2M	ketone 3 0.4M	ketone 3 0.8M	ketone 3 1.0M
2	0.0283	0.0295	0.0289	
4	0.064	0.0637	0.0652	0.0533
6	0.0866	0.105	0.1	0.0823
8	0.118	0.138	0.131	0.106
10	0.147	0.178	0.165	0.143

Zero-order rate dependency was observed on ketone **3** concentration.

(E-2)-6: Initial rate kinetics on enone **2e concentration in the presence of MS 3A.**

Procedure for the Michael reaction with 0.4 M enone **2e concentration in the presence of MS 3A.**

MS3A (75 mg) in a test tube was dried at 160 °C under vacuum (0.7 KPa) with vigorous stirring for 3h. After cooling down to room temperature, argon gas was refilled to the test tube and a solution of (*S,S*)-linked-BINOL **1** (3.39 mg, 9.4w/w% diethyl ether and hexane included, 0.005 mmol) in THF (0.3 mL) was charged. The resulting mixture was cooled to −20 °C, and Et₂Zn (20 μL, 0.02 mmol, 1.0 M in hexanes) was added. After stirring for 30 min at the same temperature, a solution of **3** (322.3 mg, 2.0 mmol) in THF (2.1 mL) was added. The resulting mixture was warmed to 0 °C, and **2e** (1.0 mmol) was added. The reaction mixture was stirred at 0 °C. Sampling and determination of chemical yields were carried out by the same procedure as described in section (E-2)-1.

Figure S(E)-6. Initial rate kinetics on enone **2e** concentration with MS3A.

Table S(E)-7. Numerical Data for Plots in Figure S(E)-6.

time (min)	yield (%)			
	2e 0.1 M	2e 0.2 M	2e 0.4 M	2e 0.8 M
5	0.0303	0.0431	0.0776	0.112
10	0.0472	0.0782	0.143	0.208
15	0.058	0.108	0.191	0.33
20	0.0675	0.119	0.25	0.401
25	0.075	0.139	0.265	0.479
30		0.149	0.314	0.563

First-order rate dependency was observed on enone **2e** concentration.

Crystal Structures.

Crystal structure and CIF file of **6a** were already reported in ref. 15.

Crystal structure of *syn*-**8g**.

Crystal structure of *syn*-**8o**.