Catalytic Intermolecular Enal-Alkyne [3+2] Reductive Cycloadditions

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Unless otherwise noted, reagents were commercially available and were used without purification. Tetrahydrofuran (THF) was treated under nitrogen using a solvent purification system (Innovative Technology, Inc., Model # SPS-400-3). Freshly distilled PBu₃ (tributylphosphine) was used in all reactions. Ni(COD)₂ (Strem Chemicals, Inc., used as received) was stored and weighed in an inert atmosphere glovebox. All reactions were conducted in flame-dried glassware under a nitrogen or argon atmosphere. ¹H and ¹³C spectra were obtained in CDCl₃ at rt, unless otherwise noted, on a Varian Mercury 400 or Varian Unity 500 MHz instrument. Chemical shifts of ¹H NMR spectra were recorded in parts per million (ppm) on the δ scale from an internal standard of residual chloroform (7.27 ppm). Chemical shifts of ¹³C NMR spectra were recorded in ppm from the central peak of CDCl₃ (77.0 ppm) on the δ scale. High resolution mass spectra (HRMS) were obtained on a VG-70-250-s spectrometer manufactured by Micromass Corp. (Manchester UK) at the University of Michigan Mass Spectrometry Laboratory.

General Procedure for the Ni(COD)₂/PBu₃ Promoted [3+2] Cycloaddition of Enals and Alkynes

To a solution of Ni(COD)₂ (0.1 equiv.) in THF (0.6 mL) was added dropwise tributylphosphine (PBu₃) (0.2 equiv.) at room temperature. After stirring for 5-10 min at rt, the reaction mixture became bright yellow. A solution of enal (1.0 equiv.) and alkyne (2.0 equiv.) at rt. in MeOH (4.4 mL) was added, and then Et₃B (4.0 equiv.) was added. The reaction mixture was stirred at 50 °C until TLC analysis indicated disappearance of the enal. The reaction mixture was concentrated in vacuo. The residue was purified via flash chromatography (SiO₂) to afford the desired product. Diastereomeric ratios were determined on crude reaction mixtures using NMR, GC or GC-MS. GC’s with FID detection were carried on an Agilent 6890N Network GC System with a HP-5MS column (30m x 0.252 mm x 0.25 μm). GCMS analyses were carried on a HP 6890 Series GC System with a HP-5MS column (30m x 0.252 mm x 0.25 μm).
(1R*,4R*)-3-Methyl-2,4-diphenylcyclopent-2-enol (Major, Table 1, entry 1)

Following the general procedure, trans-cinnamaldehyde (41 mg, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBu$_3$ (16 µL, 0.06 mmol), and Et$_3$B (174 µL, 1.20 mmol) were stirred for 3 h at 50°C. The product (42 mg, 56%, dr 81:19) was obtained as colorless oil after SiO$_2$ chromatography (20% Et$_2$O in Hexanes). $^1$H NMR (400 MHz, CDCl$_3$) δ 7.38-7.19 (m, 10H), 5.20 (m, 1H), 3.66 (t, $J = 7.2$ Hz, 1H), 2.89 (ddd, $J = 13.9, 7.8, 8.4$ Hz, 1H), 1.76 (ddd, $J = 13.9, 4.8, 6.0$ Hz, 1H), 1.73 (bs, 1H), 1.59 (t, $J = 1.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 144.6, 140.9, 140.1, 136.0, 128.6, 128.5, 128.4, 128.0, 127.0, 126.4, 78.4, 54.6, 42.4, 14.5; IR(film, cm$^{-1}$) 3400, 3024, 1599, 1494; HRMS (El) $m/z$ calculated for C$_{18}$H$_{18}$O [M$^+$] 250.1358, found 250.1366.

(1R*,4S*)-3-Methyl-2,4-diphenylcyclopent-2-enol (Minor, Table 1, entry 1)

$^1$H NMR (400 MHz, CDCl$_3$) δ 7.45-7.12 (m, 10H), 5.30 (m, 1H), 4.02 (t, $J = 6.8$ Hz, 1H), 2.31 (m, 2H), 1.77 (bs, 1H), 1.63 (s, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 144.5, 142.0, 139.8, 136.1, 128.6, 128.44, 128.37, 127.6, 127.0, 126.4, 79.3, 54.8, 43.4, 14.2; IR(film, cm$^{-1}$) 3400, 3024, 1599, 1494; HRMS (El) $m/z$ calculated for C$_{18}$H$_{18}$O [M$^+$] 250.1358, found 250.1366.

(1R*,4R*)-3-Methyl-2-phenyl-4-propylcyclopent-2-enol (Table 1, entry 2)

Following the general procedure, trans-2-hexen-1-ol (35 µL, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBu$_3$ (16 µL, 0.06 mmol), and Et$_3$B (174 µL, 1.20 mmol) were stirred for 1 h at 50°C. The product (55 mg, 85%, dr 87:13) was obtained as colorless oil after SiO$_2$ chromatography (20% Et$_2$O in Hexanes).
NMR analysis of the crude reaction mixture indicated an 87:13 product ratio (major isomer 1H signal at 5.07 ppm; minor isomer 1H signal at 5.00 ppm). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.35-7.27 (m, 4H), 7.23-7.19 (m, 1H), 5.07 (m, 1H), 2.53 (dt, $J = 12.8, 7.6$ Hz, 1H), 2.50 (m, 1H), 1.75 (s, 3H), 1.72 (m, 1H), 1.57 (bs, 1H), 1.46-1.21 (m, 4H), 0.95 (t, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 142.1, 138.5, 136.2, 128.4, 128.3, 126.6, 78.2, 47.7, 38.5, 36.8, 20.6, 14.3, 14.1; IR (film, cm$^{-1}$) 3388, 2956, 1598, 1442; HRMS (EI) m/z calcd for C$_{15}$H$_{22}$O [M$^+$] 216.1514, found 216.1509. The structural assignment of the product was confirmed by Dess-Martin oxidation followed by L-selectride reduction to re-afford the cis isomer.

(1R*,5S*)-3,5-Dimethyl-2-phenylcyclopent-2-enol (Table 1, entry 3)

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\begin{align*}
&\text{Following the general procedure, methacrolein (25 } \mu\text{L, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBU$_3$ (16 } \mu\text{L, 0.06 mmol), and Et$_3$B (174 } \mu\text{L, 1.20 mmol) were stirred for 15 minutes at 50°C. The product (45 mg, 80%, dr 90:10) was obtained as colorless oil after SiO$_2$ chromatography (20 % Et$_2$O in Hexanes).} \\
&\text{NMR analysis of the crude reaction mixture indicated an 90:10 product ratio (major isomer 1H signal at 4.64 ppm; minor isomer 1H signal at 4.80 ppm).} \\
&\text{$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.35-7.29 (m, 4H), 7.21 (m, 1H), 4.64 (m, 1H), 2.75 (dd, $J = 8.0, 16.8$ Hz, 1H), 2.11 (m, 1H), 1.95 (ddt, $J = 16.8, 5.6, 1.2$ Hz, 1H), 1.79 (d, $J = 1.2$ Hz, 3H), 1.62 (bs, 1H), 1.15 (d, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 138.3, 137.5, 136.3, 128.30, 128.28, 126.6, 86.8, 44.6, 40.9, 19.2, 15.7; IR (film, cm$^{-1}$) 3366, 2954, 1599, 1440; HRMS (EI) m/z calcd for C$_{13}$H$_{18}$O [M$^+$] 188.1201, found 188.1209.}
\end{align*}
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(1R*,4S*,5S*)-3,5-Dimethyl-2,4-diphenylcyclopent-2-enol (Table 1, entry 4)

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\begin{align*}
&\text{Following the general procedure, } \alpha\text{-methyl-}trans\text{-cinamaldehyde (44 mg, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBU$_3$ (16 } \mu\text{L, 0.06 mmol), and Et$_3$B (174 } \mu\text{L, 1.20 mmol) were stirred for 5h at 50°C. The product (45 mg, 57%, dr 81:11:8) was obtained as a white solid after SiO$_2$ chromatography (20 % Et$_2$O in Hexanes). NMR analysis of the crude reaction mixture indicated an 81:11:8 product ratio (major isomer 1H signal at 4.70 ppm; minor isomers 1H signal at 4.80 ppm and 4.65}
\end{align*}
\]
ppm). $^1$H NMR (400 MHz, CD$_2$Cl$_2$) $\delta$ 7.35 (d, $J = 7.2$ Hz, 2H), 7.26 (t, $J = 8.0$ Hz, 2H), 7.18-7.06 (m, 4H), 6.95 (d, $J = 6.8$ Hz, 2H), 4.70 (m, 1H), 3.63 (d, $J = 8.8$ Hz, 1H), 2.37 (m, 1H), 1.57 (d, $J = 0.4$ Hz, 3H), 1.16 (d, $J = 5.6$ Hz, 1H), 0.84 (d, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 140.3, 140.2, 140.1, 135.8, 128.9, 128.4, 128.3, 127.0, 126.5, 84.6, 58.5, 46.3, 14.8, 14.6; IR (film, cm$^{-1}$) 3311, 2872, 1599, 1493; HRMS (ESI) m/z calcld for C$_{19}$H$_{20}$ONa [M+Na]$^+$ 287.1412, found 287.1411.

(1R*,4S*,5S*)-3,4,5-Trimethyl-2-phenylcyclopent-2-enol (Table 1, entry 5)

Following the general procedure, trans-2-methyl-2-butenal (29 µL, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBu$_3$ (16 µL, 0.06 mmol), and Et$_3$B (174 µL, 1.20 mmol) were stirred for 2h at 50°C. The product (45 mg, 75%, dr 71:17:12) was obtained as a white solid after SiO$_2$ chromatography (20% Et$_2$O in Hexanes). NMR analysis of the crude reaction mixture indicated a 71:17:12 product ratio (major isomer 1H signal at 4.64 ppm; minor isomers 1H signal at 5.12 ppm and 4.70 ppm). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.35-7.28 (m, 4H), 7.23-7.19 (m, 1H), 4.64 (dt, $J = 5.6$, 1.6 Hz, 1H), 2.71 (quint, $J = 7.2$ Hz, 1H), 2.14 (dquint, $J = 7.2$, 6.0 Hz, 1H), 1.76 (t, $J = 1.2$ Hz, 3H), 1.54 (bs, 1H), 1.08 (d, $J = 7.2$ Hz, 3H), 0.95 (d, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 142.9, 137.4, 136.4, 128.3, 128.2, 126.6, 84.7, 45.1, 44.5, 13.8, 13.6, 13.5; IR (film, cm$^{-1}$) 3118, 2960, 1646, 1449; HRMS (ESI) m/z calcld for C$_{14}$H$_{18}$ONa [M+Na]$^+$ 225.1255, found 225.1246.

(1R*,3aR*,7aS*)-3-Methyl-2-phenyl-3a,4,5,6,7,7a-hexahydro-1H-inden-1-ol (Major, Table 1, entry 6)

Following the general procedure, 1-cyclohexene-1-carboxaldehyde (34µL, 0.30 mmol), 1-phenyl-1-propyne (70 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PBu$_3$ (16 µL, 0.06 mmol), and Et$_3$B (174 µL, 1.20 mmol) were stirred for 2h at 50°C. The product (47 mg, 68%, dr 87:13) was obtained as a white solid after SiO$_2$ chromatography (20% Et$_2$O in Hexanes). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.35-7.28 (m, 4H), 7.20 (m, 1H), 4.74 (m, 1H), 2.64 (q, $J = 6.8$ Hz, 1H), 2.08 (quint, $J = 6.4$ Hz, 1H), 1.81 (m, 1H), 1.78 (s, 3H), 1.71-1.53 (m, 2H), 1.52-1.36 (m, 4H), 1.34-1.15 (m, 2H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 143.1, 137.4, 136.7, 128.24, 128.22, 126.5, 81.3, 46.4, 45.6, 28.2, 25.3, 23.8, 23.2, 13.7;
IR (film, cm\(^{-1}\)) 3116, 2917, 1646, 1493; HRMS (ESI) m/z calcd for C\(_{16}H_{20}ONa [M+Na]^+\) 251.1412 found 251.1409. The structural assignment of the product was confirmed by Dess-Martin oxidation followed by L-selectride reduction\(^1\) to re-afford the same compound as the minor product of the catalytic reaction.

(1S*,3aR*,7aS*)-3-Methyl-2-phenyl-3a,4,5,6,7,7a-hexahydro-1H-inden-1-ol (Minor, Table 1, entry 6)

\(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.36 (m, 4H), 7.25 (m, 1H), 4.98 (m, 1H), 2.50 (q, \(J = 6.4\) Hz, 1H), 2.38 (quint, \(J = 7.2\) Hz, 1H), 1.83 (m, 3H), 1.80 (m, 1H), 1.61 (m, 4H), 1.39 (m, 4H); \(^13\)C NMR (100 MHz, CDCl\(_3\)) \(\delta\) 142.0, 138.2, 136.8, 128.4, 128.2, 126.5, 81.0, 46.2, 41.2, 28.1, 24.3, 23.5, 22.6, 13.6; IR (film, cm\(^{-1}\)) 3116, 2917, 1646, 1493; HRMS (ESI) m/z calcd for C\(_{16}H_{20}ONa [M+Na]^+\) 251.1412, found 251.1409.

(1R*,5S*)-5-Methyl-2-phenyl-3-(trimethylsilyl)cyclopent-2-enol (Table 2, entry 1)

Following the general procedure, methacrolein (25 \(\mu\)L, 0.30 mmol), 1-phenyl-2-(trimethylsilyl)acetylene (118 mg, 0.60 mmol), Ni(COD)\(_2\) (8 mg, 0.03 mmol), PBu\(_3\) (16 \(\mu\)L, 0.06 mmol), and Et\(_3\)B (174 \(\mu\)L, 1.20 mmol) were stirred for 1h at 50\(^\circ\)C. The product (45 mg, 60\%, dr 82:18) was obtained as colorless oil after SiO\(_2\) chromatography (20 \% Et\(_2\)O in Hexanes). GCMS analysis of the crude reaction mixture (start temp. 70 \(^\circ\)C, end temp. 250 \(^\circ\)C, 10 \(^\circ\)C/ min) indicated an 82:18 product ratio (major isomer retention time = 13.3 min; minor isomer retention time = 13.5 min). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.31-7.17 (m, 5H), 4.52 (d, \(J = 5.2\) Hz, 1H), 2.73 (ddd, \(J = 1.6, 7.6, 16\) Hz, 1H), 2.12 (sept, \(J = 6.8\) Hz, 1H), 2.02 (ddd, \(J = 1.6, 16.0, 6.8\) Hz, 1H), 1.56 (bs, 1H), 1.16 (d, \(J = 6.8\) Hz, 3H), -0.12 (s, 9H); \(^13\)C NMR (100 MHz, CDCl\(_3\)) \(\delta\) 154.9, 141.4, 138.4, 128.5, 128.0, 127.2, 88.4, 43.3, 42.5, 18.6, -0.9; IR (film, cm\(^{-1}\)) 3332, 2954, 1591, 1442, 1248; HRMS (EI) m/z calcd for C\(_{15}H_{22}OSi [M^+]\) 246.1440, found 246.1437.
(1R*,5S*)-2-(4-Methoxyphenyl)-5-methyl -3-(trimethylsilyl)cyclopent-2-enol (Table 2, entry 2)

Following the general procedure, methacrolein (25 μL, 0.30 mmol), (4-methoxyphenylethynyl)trimethylsilane (130 μL, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBu₃ (16 μL, 0.06 mmol), and Et₂B (174 μL, 1.20 mmol) were stirred for 2h at 50°C. The product (57 mg, 69 %, dr 90:10) was obtained as light yellow oil after SiO₂ chromatography (20 % Et₂O in Hexanes). NMR analysis of the crude reaction mixture indicated an 90:10 product ratio (major isomer 1H signal at 4.54 ppm; minor isomer 1H signal at 4.60 ppm). ¹H NMR (400 MHz, CDCl₃) δ 7.17 (m, 2H), 6.87 (m, 2H), 4.54 (d, J = 5.6 Hz, 1H), 3.82 (s, 3H), 2.76 (ddd, J = 1.6, 7.6, 16.0 Hz, 1H), 2.14 (sept, J = 6.8 Hz, 1H), 2.05 (ddd, J = 1.6, 16.4, 6.8 Hz, 1H), 1.57 (bs, 1H), 1.20 (d, J = 6.8 Hz, 3H), -0.06 (s, 9H); ¹³C NMR (100 MHz, CDCl₃) δ 158.9, 154.5, 140.5, 130.6, 129.6, 113.4, 88.3, 55.2, 43.2, 42.5, 18.6, -0.8; IR (film,cm⁻¹) 3365, 2954, 2912, 1508, 1247; HRMS (EI) m/z calcd for C₁₆H₂₃O₂Si [M⁺] 276.1546, found 276.1543.

(1R*,4S*)-2-(4-Methoxyphenyl)-4-propyl -3-(trimethylsilyl)cyclopent-2-enol (Table 2, entry 3)

Following the general procedure, trans-2-hexen-1-ol (35 μL, 0.30 mmol), (4-methoxyphenylethynyl)trimethylsilane (130 μL, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBu₃ (16 μL, 0.06 mmol), and Et₂B (174 μL, 1.20 mmol) were stirred for 4h at 50°C. The product (71 mg, 78 %, dr 92:8) was obtained as light yellow oil after SiO₂ chromatography (20 % Et₂O in Hexanes). NMR analysis of the crude reaction mixture indicated a 92:8 product ratio (major isomer 1H signal at 5.00 ppm; minor isomer 1H signal at 4.88 ppm). ¹H NMR (400 MHz, CDCl₃) δ 7.18 (m, 2H), 6.88 (m, 2H), 5.00 (m, 1H), 3.83 (s, 3H), 2.83 (m, 1H), 2.50 (dt, J = 14.0, 8.0 Hz, 1H), 1.72 (m, 1H), 1.54-1.44 (m, 2H), 1.36-1.20 (m, 3H), 0.96 (t, J = 7.2 Hz, 3H), -0.05 (s, 9H); ¹³C NMR (100 MHz, CDCl₃) δ 159.1, 155.0, 145.6, 130.5, 129.8, 113.5, 81.0, 55.2, 49.0, 39.6, 38.6, 20.8, 14.2, 0.1; IR (film,cm⁻¹) 3425, 2956, 1612, 1508, 1247; HRMS (ESI) m/z calcd for C₁₈H₃₅O₂SiNa [M+Na⁺] 327.1756, found 327.1758.
4,4-Dimethyl-2-phenylcyclopent-2-enol (Table 2, entry 4)

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O
H
Me
Me
Ph
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Following the general procedure, 3-methyl-2-buten-1-al (30 μL, 0.30 mmol), phenylacetylene (67 μL, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBU₃ (16 μL, 0.06 mmol), and Et₃B (174 μL, 1.20 mmol) were stirred for 8h at 50°C. The product (34 mg, 60 %) was obtained as yellow oil after SiO₂ chromatography (20 % Et₂O in Hexanes). ¹H NMR (400 MHz, CDCl₃) δ 7.56 (m, 2H), 7.36 (m, 2H), 7.27 (m, 1H), 6.13 (s, 1H), 5.28 (dd, J = 3.2, 7.2 Hz, 1H), 2.27 (dd, J = 7.2, 14.0 Hz, 1H), 1.81 (dd, J = 3.2, 13.6 Hz, 1H), 1.60 (bs, 1H), 1.28 (s, 3H), 1.15 (s, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 141.4, 140.4, 134.6, 128.5, 127.4, 126.2, 77.1, 49.5, 43.6, 30.3, 29.2; IR (film, cm⁻¹) 3351, 2951, 1598, 1446; HRMS (ESI) m/z calcd for C₁₃H₁₀ONa [M+Na]⁺ 211.1099, found 211.1096.

(1R*, 5S*)-5-Methyl-2,3-diphenylcyclopent-2-enol (Table 2, entry 5)

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O
H
H₃C
H
H
Ph
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Following the general procedure, methacrolein (25 μL, 0.30 mmol), diphenylacetylene (107 mg, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBU₃ (16 μL, 0.06 mmol), and Et₃B (174 μL, 1.20 mmol) were stirred for 2h at 50°C. The product (23 mg, 30 %, dr 84:16) was obtained as colorless oil after SiO₂ chromatography (20 % Et₂O in Hexanes). NMR analysis of the crude reaction mixture indicated an 84:16 product ratio (major isomer 1H signal at 4.49 ppm; minor isomer 1H signal at 4.66 ppm). ¹H NMR (400 MHz, C₆D₆) δ 7.32-6.95 (m, 10H), 4.49 (m, 1H), 2.93 (m, 1H), 2.14 (m, 2H), 1.33 (d, 1H), 1.09 (d, J = 6.8 Hz, 3H); ¹³C NMR (100 MHz, C₆D₆) δ 140.6, 139.3, 138.3, 137.6, 129.7, 129.0, 128.9, 128.7, 127.8, 127.6, 87.9, 43.4, 41.6, 19.3; IR (film, cm⁻¹) 3344, 2954, 1598, 1492, 1443; HRMS (ESI) m/z calcd for C₁₈H₁₈ONa [M+Na]⁺ 273.1255, found 273.1258.

(Z)-2-Methyl-4,5-diphenylpent-4-enal (Table 2, entry 5)

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O
H
CH₃
Ph
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Following the general procedure, methacrolein (25 μL, 0.30 mmol), diphenylacetylene (107 mg, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBU₃ (16 μL, 0.06 mmol), and Et₃B (174 μL, 1.20 mmol) were stirred for 2h at 50°C. The product (45 mg, 60 %) was obtained as a colorless oil after SiO₂ chromatography (20 % Et₂O in Hexanes). ¹H NMR (400 MHz, CDCl₃) δ 9.59 (d, J = 1.6 Hz, 1H), 7.30-7.22 (m, 3H), 7.13 (m, 2H), 7.07 (m,
3H), 6.90 (m, 2H), 6.46 (s, 1H), 3.00 (ddd, $J = 1.2, 5.6, 13.6$ Hz, 1H), 2.42 (ddd, $J = 0.8, 8.8, 13.6$ Hz, 1H), 2.34 (m, 1H), 1.08 (d, $J = 6.8$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 204.5, 139.8, 139.4, 136.8, 129.0, 128.80, 128.77, 128.6, 127.9, 127.4, 126.5, 44.2, 41.6, 13.0; IR (film, cm$^{-1}$) 2930, 2718, 1722, 1599, 1442; HRMS (ESI) m/z calcd for C$_{18}$H$_{15}$ONa [M+Na]$^+$ 273.1255, found 273.1255.

(1R*,4R*)-2,3-Diphenyl-4-propylcyclopent-2-enol (Major, Table 2, entry 6)

Following the general procedure, trans-2-hexen-1-ol (35 µL, 0.30 mmol), phenyacetylene (107 mg, 0.60 mmol), Ni(COD)$_2$ (8 mg, 0.03 mmol), PbU$_3$ (16 µL, 0.06 mmol), and Et$_3$B (174 µL, 1.20 mmol) were stirred for 1 h at 50°C. The product (62 mg, 74 %, dr 82:18) was obtained as white solid after SiO$_2$ chromatography (20 % Et$_2$O in Hexanes). $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.25-7.09 (m, 10H), 4.98 (dt, $J = 3.6, 7.2$ Hz, 1H), 3.02 (septet, $J = 4.0$ Hz, 1H), 2.63 (dt, $J = 14.0, 8.0$ Hz, 1H), 1.81 (d, $J = 6.8$ Hz, 1H), 1.66 (dt, $J = 13.6, 4.0$ Hz, 1H), 1.60-1.50 (m, 1H), 1.40 (m, 1H), 1.32-1.19 (m, 2H), 0.83 (t, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 146.3, 139.2, 137.2, 136.5, 128.8, 128.7, 128.1, 128.0, 127.0, 126.8, 79.9, 47.2, 38.7, 37.3, 21.0, 14.1; IR (film, cm$^{-1}$) 3364, 2955, 1612, 1442; HRMS (ESI) m/z calcd for C$_{20}$H$_{22}$ONa [M+Na]$^+$ 301.1568, found 301.1557. The structural assignment of the product was confirmed by Dess-Martin oxidation followed by L-selectride reduction$^1$ to re-afford the cis isomer.

(1R*,4S*)-2,3-Diphenyl-4-propylcyclopent-2-enol (Minor, Table 2, entry 6)

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.22-7.05 (m, 10H), 5.34 (m, 1H), 3.35 (m, 1H), 2.15 (m, 2H), 1.63 (d, $J = 4.8$ Hz, 1H), 1.45-1.28 (m, 2H), 1.25-1.16 (m, 1H), 1.05 (m, 1H), 0.79 (t, $J = 7.2$ Hz, 3H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 145.4, 139.4, 136.9, 135.4, 128.8, 128.5, 128.3, 128.2, 126.99, 126.95, 79.1, 47.2, 38.7, 36.1, 20.4, 14.2; IR (film, cm$^{-1}$) 3364, 2955, 1612, 1442; HRMS (ESI) m/z calcd for C$_{20}$H$_{22}$ONa [M+Na]$^+$ 301.1568, found 301.1557.
(1R*,4R*)-2,3-Diethyl-4-propylcyclopent-2-enol (Major, Table 2, entry 7)

Following the general procedure, trans-2-hexen-1-ol (35 µL, 0.30 mmol), 3-hexyne (68 µL, 0.60 mmol), Ni(COD)₂ (8 mg, 0.03 mmol), PBU₃ (16 µL, 0.06 mmol), and Et₃B (174 µL, 1.20 mmol) were stirred for 3h at 50°C. The product (35 mg, 64 %, dr 63:37) was obtained as colorless oil after SiO₂ chromatography (20 % Et₂O in Hexanes). ¹H NMR (400 MHz, CDCl₃) δ 4.65 (t, J = 5.6 Hz, 1H), 2.48 (m, 1H), 2.42 (dt, J = 13.2, 7.6 Hz, 1H), 2.15 (m, 3H), 1.98 (sext, J = 7.6 Hz, 1H), 1.65 (m, 1H), 1.44-1.19 (m, 4H), 1.10 (m, 1H), 1.01 (t, J = 7.6 Hz, 3H), 0.95 (t, J = 7.6 Hz, 3H), 0.92 (t, J = 7.2 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 144.1, 138.7, 77.5, 43.7, 39.1, 36.8, 20.7, 19.4, 18.6, 14.3, 13.3, 13.2; IR (film, cm⁻¹) 3325, 2961, 1653, 1559, 1457; HRMS (El) m/z calcd for C₁₂H₂₂O [M⁺] 182.1671, found 182.1679.

(1R*,4S*)-2,3-Diethyl-4-propylcyclopent-2-enol (Minor, Table 2, entry 7)

¹H NMR (400 MHz, CDCl₃) δ 4.71 (bs, 1H), 2.78 (m, 1H), 2.15 (m, 2H), 1.96 (sext, J = 7.2 Hz, 1H), 1.82 (m, 2H), 1.60-1.52 (m, 2H), 1.38-1.15 (m, 4H), 1.01 (t, J = 7.6 Hz, 3H), 0.98 (t, J = 7.6 Hz, 3H), 0.91 (t, J = 7.6 Hz, 3H); ¹³C NMR (100 MHz, CDCl₃) δ 144.6, 138.6, 77.9, 43.6, 39.8, 36.1, 20.3, 19.3, 18.7, 14.3, 13.3, 12.7; IR (film, cm⁻¹) 3325, 2961, 1653, 1559, 1457; HRMS (El) m/z calcd for C₁₂H₂₂O [M⁺] 182.1671, found 182.1679.

3-Phenyl-1,2,4,5,5a,6,7,8-octahydro-cyclopenta[c]pentalen-2-ol

Following the general procedure, 2-[2-(4-phenyl-but-3-ynyl)-cyclopentylidene]-acetaldehyde² (15 mg, 0.064 mmol), Ni(COD)₂ (2 mg, 0.006 mmol), PBU₃ (3 µL, 0.012 mmol), and Et₃B (37 µL, 0.26 mmol) were stirred for 3h at 50°C. The product (11 mg, 72
%) was obtained as white solid after SiO₂ chromatography (30 % Et₂O in Hexanes). Spectroscopic data were identical to that previously reported and the structural assignment was confirmed by single crystal X-Ray analysis.

3-Methyl-1,2,4,5,5a,6,7,8-octahydro-cyclopenta[c]pentalen-2-ol

\[ \text{3-Methyl-1,2,4,5,5a,6,7,8-octahydro-cyclopenta[c]pentalen-2-ol} \]

\[ \text{11b} \]

Following the general procedure, 2-(2-(pent-3-ynyl)cyclopentylidene)acetaldehyde² (70 mg, 0.40 mmol), Ni(COD)₂ (11 mg, 0.04 mmol), PBu₃ (19 µL, 0.08 mmol), and Et₃B (232 µL, 1.60 mmol) were stirred for 3h at 50°C. The product (47 mg, 67 %) was obtained as light yellow color oil after SiO₂ chromatography (30 % Et₂O in Hexanes). \(^1\)H NMR (400 MHz, CDCl₃) δ 4.56 (d, \(J = 6.4 \text{ Hz}, 1\text{H}\)), 2.11 (m, 2H), 1.95 (m, 4H), 1.82-1.72 (m, 3H), 1.70 (d, \(J = 1.2 \text{ Hz}, 3\text{H}\)), 1.68-1.54 (m, 3H), 1.44 (s, 1H), 1.33 (m, 1H), \(^13\)C NMR (100 MHz, CDCl₃) δ 155.0, 127.6, 85.4, 64.1, 49.7, 47.7, 41.6, 35.4, 35.2, 27.6, 22.9, 12.4; IR (film, cm\(^{-1}\)) 3333, 2942, 1699, 1447; HRMS (EI) \(m/z\) calcd for \(\text{C}_{12}\text{H}_{18}\text{O}\) [M⁺] 178.1358, found 178.1350. NOE data were consistent with the proposed structure and the assignment was deemed secure by similarity of \(^1\)H NMR J values and chemical shifts to compound 11a.

Table 1, entry 2
Table 2, entry 5