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Supporting Information

Structure-Activity Relationships in Group 3 Metal Catalysts for Asymmetric Intramolecular Alkene Hydroamination. An Investigation of Ligands Based on the Axially Chiral 1,1'-Binaphthyl-2,2'-diamine Motif.

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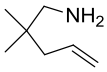
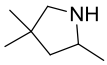
General Information: All manipulations were performed under an argon atmosphere, using standard Schlenk line techniques or in an argon-filled dry-box. Benzene-d_6, tetrahydrofuran, and dioxane were doubly distilled from sodium prior to use. Dichloromethane was distilled from calcium hydride prior to use. Dimethylformamide was distilled from calcium hydride under reduced pressure. Melting points were obtained using a Mel-Temp apparatus and are uncorrected. ^{1}H, ^{13}C, and ^{31}P NMR spectra were recorded on a Bruker DPX-300 (300 MHz) or DRX-500 (500 MHz) spectrometers. ^{1}H NMR chemical shifts (δ) are reported in parts per million (ppm) downfield of TMS. Chemical shifts for carbon are reported in parts per million downfield of TMS. Data are represented as follows: chemical shift, multiplicity (br = broad, s = singlet, d = doublet, t = triplet, m = multiplet), integration, and coupling constants in Hertz (Hz). Infrared (IR) spectra were recorded on a Jasco FT/IR-4100. High-resolution mass spectra (HRMS) were obtained from Bruker MicroTOF with an Agilent 1100 HPLC.

Materials: Aminoalkene substrate 2,2-dimethyl-1-aminopent-4-ene (**1**)[1] was synthesized as previously reported. Proligands **3a**[2] and **3c**[3] were prepared as previously reported. Trimethylsilylmethyllithium was obtained from Aldrich Chemical Co. as a 1 M solution in pentane. The solid organolithium was subsequently isolated in vacuo using Schlenk line techniques.

Experimental Procedures:

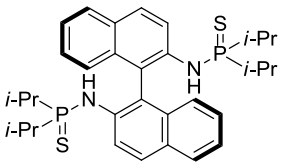


2,2-Dimethyl-1-aminopent-4-ene (**1**). Prepared as previously described.[1]
^{1}H NMR (500 MHz, C_6D_6), δ: 5.84 (ddt, 1 H, *J* = 16.5, 10.5, 7.5 Hz), 5.09 (m, 2 H), 2.35 (s, 3 H), 1.98 (d, 2 H, *J* = Hz), 0.84 (s, 6 H), 0.55 (br s, 2 H).



2,4,4-Trimethylpyrrolidine (**2**).[4]
^{1}H NMR (300 MHz, C_6D_6), δ: 3.22 (m, 1 H), 2.77 (m, 1 H), 2.62 (m, 1 H), 1.63 (dd, 1 H, *J* = 12.3, 6.9 Hz), 1.21 (br s, 1 H), 1.19 (d, 3 H, *J* = 6.0 Hz), 1.05 (s, 3 H), 0.99 (s, 3 H).

Proligand Syntheses:



Proligand **3a** was prepared as previously described.[2] ^{1}H{^{31}P} NMR (300 MHz, $CDCl_3$), δ: 8.29 (d, 2 H, *J* = 9.0 Hz), 7.89 (d, 2 H, *J* = 9.0 Hz), 7.86 (d, 2 H, *J* = 7.8 Hz), 7.32 (t, 2 H, *J* = 6.9 Hz), 7.29 (m, 2 H), 7.07 (d, 2 H, *J* = 8.7 Hz), 4.29 (d, 2 H, *J* = 7.8 Hz), 1.94 (m, 4 H), 1.2-0.8 (m, 24 H).

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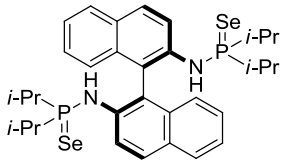
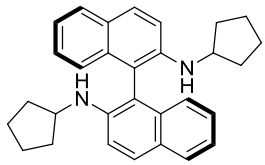
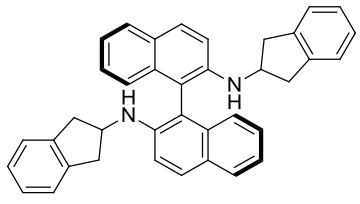


Proligand **3b**. A 25 mL round-bottom flask equipped with a magnetic stirring bar was charged with (*S*)-(-)-1,1'-binaphthyl-2,2'-diamine (0.290 g, 1.0 mmol, 1.0 equiv.) and placed under an atmosphere of argon. Tetrahydrofuran (10 mL) was added via syringe and the solution was cooled to 0 °C. *n*-Butyllithium (0.9 mL of 2.3 M in hexanes, 2.0 mmol, 2.0 equiv.) was added dropwise . The resultant orange-red solution was warmed to 22 °C and stirred for 1 h. The volatiles were removed in vacuo to provide a dark brown residue which was suspended in toluene (10 mL). The mixture was treated with chlorodiisopropylphosphine (330 μL, 2.1 mmol, 2.1 equiv.) and then heated at reflux for 3 h. The mixture was cooled to 22 °C, selenium powder (0.167 g, 2.11 mmol, 2.11 equiv.) was added and the mixture was heated at reflux for 12 h. The mixture was cooled to 22 °C and filtered. The filtrate was concentrated and the residue was purified by column chromatography (silica gel, 10% ethyl acetate in hexanes for elution). The resultant off-white solid was subsequently recrystallized from methylcyclohexane to provide **3b** as a light brown solid (0.603 g, 89%). mp = 205 °C. $^{1}H\{^{31}P\}$ NMR (500 MHz, $CDCl_3$), δ: 8.25 (d, 2 H, *J* = 9.0 Hz), 7.92 (d, 2 H, *J* = 9.0 Hz), 7.85 (d, 2 H, *J* = 8.0 Hz), 7.33 (t, 2 H, *J* = 8.0 Hz), 7.25 (t, 2 H, *J* = 7.0 Hz), 7.06 (d, 2 H, *J* = 8.5 Hz), 4.31 (m, 2 H), 2.03 (m, 4 H), 1.1-07 (m, 24 H). ^{31}P NMR (125 MHz, $CDCl_3$), δ: 81.8 (side bands due to ^{31}P-^{77}Se coupling: *J* = 390 Hz). $^{13}C\{^{31}P\}$ NMR (125 MHz, $CDCl_3$), δ: 139.1, 132.9, 129.6, 129.0, 128.3, 127.3, 124.4, 124.4, 120.4, 117.9, 32.1 (d, J_{CP} = 52.3 Hz), 30.7 (d, J_{CP} = 53.2 Hz), 16.9 (d, J_{CP} = 11.1 Hz), 16.5 (d, J_{CP} = 6.0 Hz). FTIR (neat), cm^{-1}: 3344, 3056, 2964, 2931, 2870, 1619, 1593, 1509, 1476, 1465, 1406, 1336, 1277, 1245, 1028, 994, 820, 735, 670. HRMS (ESI): calculated for $C_{32}H_{42}N_2P_2Se_2$ $[M+H]^+$: 677.1233 and 675.1236, found: 677.1209 and 675.1249.

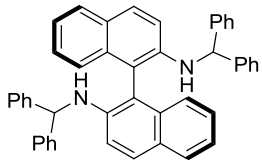


Proligand **3c** was prepared as previously described.[3] ^{1}H NMR (500 MHz, $CDCl_3$), δ: 7.91 (d, 2 H, *J* = 9.0 Hz), 7.82 (d, 2 H, *J* = 8.0 Hz), 7.35 (d, 2 H, *J* = 8.5 Hz), 7.30 (d, 2 H, *J* = 9.0 Hz), 7.19 (t, 2 H, *J* = 7.0 Hz), 7.12 (t, 2 H, *J* = 8.5 Hz), 3.87 (d, 2 H, *J* = 8.0 Hz), 3.78 (m, 2 H), 1.71 (m, 2 H), 1.63 (m, 2 H), 1.24 (m, 8 H), 1.10 (m, 2 H), 1.02 (m, 2 H).



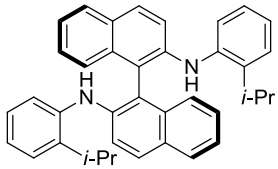
Proligand **3d**. An oven-dried 50 mL round-bottom flask equipped with a magnetic stirring was charged with (*R*)-(+)-1,1'-binaphthyl-2,2'-diamine (0.284 g, 1 mmol, 1 equiv.), 2-indanone (0.528 g, 4 mmol, 4 equiv.) and subsequently placed under an argon atmosphere. Tetrahydrofuran (12 mL) and 20% aqueous sulfuric

acid (2 mL) were added via syringe. The light brown solution was then allowed to stir at 22 °C for 2 h. The reactant mixture was cooled to 0 °C and sodium borohydride (0.532 g, 4 mmol, 4 equiv.) was added portion wise. After stirring at 22 °C for 1 h, the mixture was poured into 2% aqueous potassium hydroxide (200 mL). The aqueous layer was extracted with diethyl ether (3 X 150 mL). The combined organic layers were dried over magnesium sulfate and concentrated. The residue was purified by column chromatography (silica gel, 5% ethyl acetate in hexanes for elution) to provide **3d** as a white solid (0.217 g, 42%). mp = 210 ºC (dec.). ^{1}H NMR (500 MHz, $CDCl_3$), δ: 7.86 (d, 2 H, *J* = 9.0 Hz), 7.75 (d, 2 H, *J* = 8.0 Hz), 7.30 (d, 2 H, *J* = 8.5 Hz), 7.24 (m, 2 H), 7.16 (m, 2 H), 7.02 (m, 6 H), 6.92 (m, 4 H), 4.43 (t, 2 H, *J* = 6.5 Hz), 3.22 (dt, 4 H, *J* = 15.5, 7.0 Hz), 2.6-2.4 (m, 4 H). ^{13}C NMR (125 MHz, $CDCl_3$), δ: 143.9, 140.9, 133.8, 129.7, 128.0, 127.8, 126.8, 126.5, 124.6, 124.5, 123.9, 122.1, 114.8, 54.9, 40.4. FTIR (neat), cm^{-1}: 3397, 3052, 3022, 2936, 2904, 2838, 1618, 1598, 1511, 1483, 1425, 1350, 1333, 1297, 1249, 1214, 1150, 908, 811, 740. HRMS (ESI): calculated for $C_{38}H_{32}N_2$ $[M+H]^+$: 517.2599, found: 517.2630.



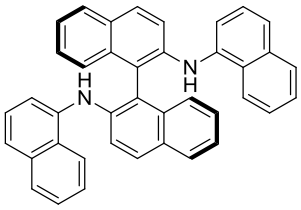
Proligand **3e**. An oven-dried 10 mL round-bottom flask equipped with a magnetic stirring bar was charged with (*R*)-(+)-1,1'-binaphthyl-2,2'-diamine (0.142 g, 0.5 mmol, 1 equiv.). The flask was attached to a reflux condenser and placed under argon. Dimethylformamide (1 mL) was added via syringe. Diphenylmethyl chloride (0.195 mL, 1.1 mmol, 2.2 equiv.) was then added via syringe to the solution. The clear, colorless solution was then heated at 100 °C for 12 h. Following heating, the solution was cooled to 22 °C and poured into water (5 mL). The aqueous layer was extracted with dichloromethane (2 X 10 mL). The organic layers were combined and washed with 10% aqueous lithium chloride (2 X 10 mL). The organic layer was then dried over magnesium sulfate and concentrated. The red-brown residue was purified by column chromatography (silica gel, 1% → 3% ethyl acetate in hexanes for elution). The resultant yellow oil was recrystallized from ethyl acetate in hexanes to provide **3e** as yellow solids (90 mg, 29%). mp = 232 °C. ^{1}H NMR (500 MHz, $CDCl_3$), δ: 7.70 (m, 4 H), 7.17 (m, 20 H), 7.06 (m, 8 H), 5.71 (s, 2 H), 4.46 (s, 2 H). ^{13}C NMR (125 MHz, $CDCl_3$), δ: 143.6, 142.8, 142.6, 133.7, 129.6, 128.7, 128.5, 128.1, 127.7, 127.4, 127.3, 127.2, 126.6, 124.2, 122.1, 114.6, 112.2, 62.1. FTIR (neat), cm^{-1}: 3410, 3057, 3027, 1619, 1596, 1510, 1492, 1453, 1347, 1296, 1265, 809, 769, 739, 662. HRMS (ESI): calculated for $C_{46}H_{36}N_2$ $[M+H]^+$: 617.2951, found: 617.2952.

Synthesis of R = Aryl; Proligands **3f and 3g**. **3f**[5] is a representative example.



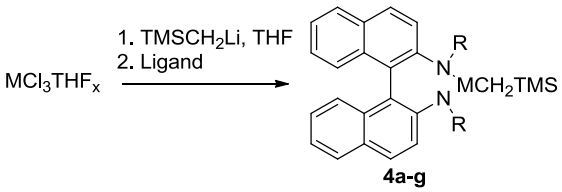
Proligand **3f**. A 25 mL round-bottom flask equipped with a magnetic stirring bar was charged with (*R*)-(+)-1,1'-binaphthyl-2,2'-diamine (0.207 g,

0.73 mmol, 1.0 equiv.), 1-bromo-2-isopropylbenzene (0.319 g, 1.6 mmol, 2.2 equiv.), tris (dibenzylideneacetone)dipalladium(0)·$CHCl_3$ (0.027 g, 0.029 mmol, 0.04 equiv.), 2,2'-bis(diphenylphosphino)-1,1'-binaphthalene (0.018 g, 0.029 mmol, 0.04 equiv.), and sodium *t*-butoxide (0.196 g, 2.04 mmol, 2.8 equiv.). The flask was evacuated and placed under an atmosphere of argon and then charged with *o*-xylene (5 mL). The reactant mixture was heated to 150 °C with stirring for 1 d. After cooling to 22 °C, water was added (10 mL) and the aqueous layer was extracted with diethyl ether (2 X 10 mL). The organic layers were combined, dried over magnesium sulfate and concentrated. The residue was purified by column chromatography (silica gel, 1% diethyl ether in hexanes for elution) to provide **3f** as a white solid (0.352 g, 93%). mp = 142 ºC. ^{1}H NMR (300 MHz, $CDCl_3$), δ: 7.87 (m, 4 H), 7.44 (d, 2 H, *J* = 9.0 Hz), 7.30 (m, 8 H), 7.23 (m, 2 H), 7.16 (t, 2 H, *J* = 7.8 Hz), 7.09 (t, 2 H, *J* = 7.5 Hz), 5.52 (br s, 2 H), 2.80 (septet, 2 H, *J* = 6.9 Hz), 0.97 (d, 6 H, *J* = 6.9 Hz), 0.81 (d, 6 H, *J* = 6.9 Hz). ^{13}C NMR (125 MHz, $CDCl_3$), δ: 141.8, 141.6, 139.0, 133.9, 129.4, 128.8, 128.2, 127.0, 126.4, 126.0, 124.1, 124.0, 122.9, 122.6, 116.5, 114.3, 27.7, 22.5. FTIR (neat), cm^{-1}: 3400, 3054, 2962, 1618, 1594, 1502, 1419, 1340, 1297, 909, 815, 748, 730. HRMS (ESI): calculated for $C_{38}H_{36}N_2$ $[M+H]^+$: 521.2951, found: 521.2922.



Proligand **3g**. Pale yellow solid (92%). mp = 150 ºC. ^{1}H NMR (300 MHz, $CDCl_3$), δ: 7.87 (m, 6 H), 7.77 (d, 2 H, *J* = 8.4 Hz), 7.63 (d, 2 H, *J* = 7.8 Hz), 7.5-7.3 (m, 14 H), 7.30 (m, 2 H), 6.05 (br s, 2 H). ^{13}C NMR (125 MHz, $CDCl_3$), δ: 142.1, 138.0, 134.6, 134.0, 129.6, 129.1, 129.0, 128.4, 128.3, 127.2, 126.1, 125.9, 124.3, 124.1, 123.3, 122.1, 118.6, 117.3, 114.9. FTIR (neat), cm^{-1}: 3383, 3052, 1618, 1594, 1576, 1509, 1487, 1417, 1398, 1340, 1293, 907, 815, 792, 780, 733. HRMS (ESI): calculated for $C_{40}H_{28}N_2$ $[M+H]^+$: 537.2286, found: 537.2312.

Preparation and Use of Organometallic Precatalysts (4a-g).

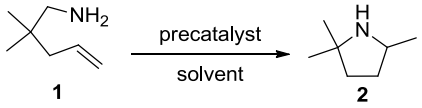


4a-g

In an argon-filled dry-box, $MCl_3(THF)_x$ (0.016 mmol, 1.0 equiv.), trimethylsilylmethyllithium (5.1 mg or 54 μL of a 1 M solution in *p*-xylene, 0.054 mmol, 3.4 equiv.)*, and tetrahydrofuran (0.5 mL) were combined in a J. Young NMR tube. The solution was shaken for five minutes prior to addition of an enantiopure binaphthyl-

* See **Table S-1** for Optimization of Precatalyst Synthesis

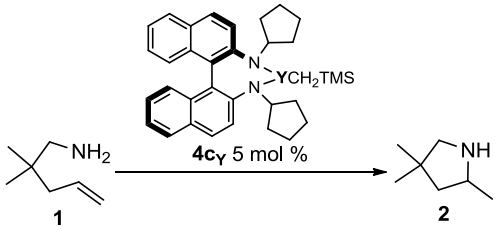
derived proligand (0.016 mmol, 1.0 equiv.). The resulting yellow solution was then allowed to complete ligand exchange for twelve hours (generally time beyond 1 h was unnecessary). Following completion of the ligand exchange the solvent was removed in vacuo and the residue was treated with C_6D_6 (0.5 mL) and the aminoalkene substrate **1** (36 mg, 0.32 mmol, 20 equiv.).



Hydroamination Assay. Following addition of the **1** to the precatalysts (described above) the resulting reaction mixture was monitored by ^{1}H NMR spectroscopy until judged >95% conversion.

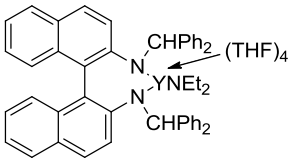
Enantioselectivity Determination. Following completion of the cyclization, the crude product mixture was diluted with dichloromethane (0.5 mL). Then 250 μL of the mixture was added to *R*-(-)-*O*-acetylmandelic acid (0.017 mg, 0.085 mmol). The solution was concentrated to provide the scalemic 2,4,4-trimethyl-pyrrolidin-1-yl salt of (*R*)-(-)- *O*-acetylmandelic acid.[6] ^{1}H NMR (500 MHz, $CDCl_3$), δ: (Key Resonances) 3.14 (m, 1 H, **2-(*R*)**); 2.93 (m, 3 H, 1 H – **2-(*R*)** and 2 H – **2-(*S*)**).

Table S-1. Reaction Optimization



entry	Preligand equiv.	$TMSCH_2Li$ equiv.	solvent	T (°C)	t[a]	ee[b]
1	1	3.4	dioxane	60	1 d	66
2	1	4.0	dioxane	60	3 d	70
3	1	3.0	THF	22	20 d	50
4	1	3.0	C_6D_6	22	4 d	62
5	1	3.4	C_6D_6	22	2 d	70
6	1	4.0	C_6D_6	22	26 h	64

[a]>95% conversion as determined by ^{1}H NMR Spectroscopy.
[b]Enantiomeric excess.



Complex $6e_Y \cdot (THF)_4 \cdot (LiCl)_2$. In an argon-filled dry-box, $YCl_3(THF)_{3.5}$ (7.16 mg, 0.016 mmol, 1.0 equiv.), trimethylsilylmethyllithium (5.1 mg, 0.054 mmol, 3.4 equiv.), and tetrahydrofuran (0.5 mL) were combined in a J. Young NMR tube. The solution was shaken for five minutes prior to addition of a proligand **3e** (9.86 mg, 0.016 mmol, 1.0 equiv.). The yellow solution was monitored until all of **3e** was ligated (10 h, 22 °C). Diethylamine (1.8 μL, 0.016 mmol, 1.0 equiv.) was added. The solution was subsequently shaken for five minutes. The light brown solution was transferred into a swivel frit apparatus. The solvent was removed to provide a light brown residue. The residue was diluted with diethyl ether (5 mL) and filtered to provide $\mathbf{6e_Y \cdot (THF)_4 \cdot (LiCl)_2}$ as a yellow solid (15 mg, 82%). ^{1}H NMR (500 MHz, C_6D_6), δ: 7.64 (m, 6 H), 7.50 (d, 2 H, *J* = 9.5 Hz), 7.30 (t, 4 H, *J* = 7.5 Hz), 7.3-7.1 (m, 11 H), 7.1-7.0 (m, 9 H), 5.92 (s, 2 H), 3.4 (m, 4 H), 3.27 (m, 8 H), 3.12 (m, 8 H), 1.40 (m, 6 H), 1.25 (m, 16 H). ^{13}C NMR (125 MHz, THF), δ: 155.2, 149.7, 146.4, 137.0, 128.4, 128.4, 128.1, 127.6, 126.7, 125.8, 125.6, 125.5, 124.7, 124.6, 118.0, 117.3, 115.0, 65.7, 44.0, 15.0. FTIR (neat), cm^{-1}: 3053, 3021, 2960, 2877, 1609, 1589, 1496, 1449, 1421, 1338, 1290, 1151, 1044, 1025, 808, 771, 743, 701. Anal. Calcd for $C_{66}H_{76}Cl_2Li_2N_3O_4Y$: C, 68.99; H, 6.67; N, 3.66. Found: C, 68.73; H, 6.25; N, 3.06.

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[2] J. Y. Kim, T. Livinghouse and Y. Horino, *J. Am. Chem. Soc.*, 2003, **125**, 9560.
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