SHORT COMMUNICATION

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Rhodium-Catalyzed Alkene Hydrosilylation via a Hydride Shuttle Process by Diene Ligands: Dramatic Enhancement of Regio- and Diastereoselectivity

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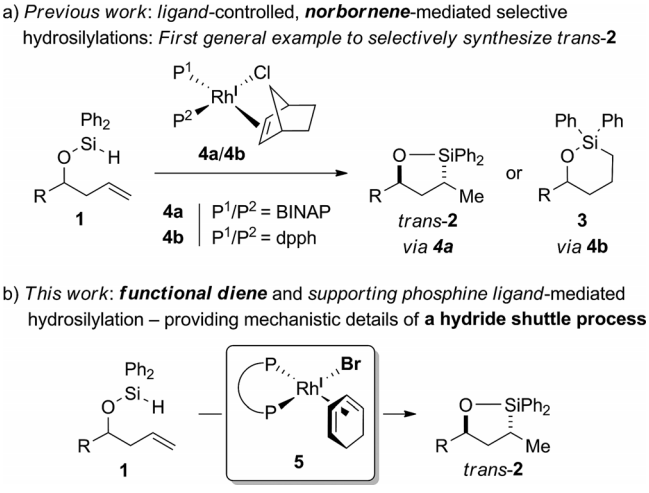
Dedicated to Professor Chan-Mo Yu (Sungkyunkwan University) on the occasion of his 60th birthday

Keywords: Homogeneous catalysis / Rhodium / Hydrosilylation / Hydride shuttle / Diene ligands / Cyclization

A cooperative ligand-assisted, Rh-catalyzed intramolecular alkene hydrosilylation of homoallylic silyl ethers (**1**) was developed to provide 1,3-*trans*-oxasilacyclopentanes (*trans*-**2**) in a highly regio- and diastereoselective manner. The modification of metal-ligand architecture employing an inner-sphere functional diene ligand (1,3-cyclohexadiene) and a supporting phosphine ligand (BINAP) was identified as responsible for dramatic enhancement of selectivities. Mechanistic details of a diene ligand-mediated *hydride shuttle process* are presented as the potential mechanistic driving force behind the high level of the selectivities.

Introduction

Transition metals ligated with precisely designed ligands[1] are versatile platforms for a wide array of catalytic processes.[2] Readily modifiable metal-ligand architectures often render unprecedented reactivity and selectivity to molecular catalysis by controlling electronic and steric properties of the catalyst through engaging favorable coordination.[3] Our laboratory recently disclosed ligand-controlled, norbornene-mediated, regio- and diastereoselective rhodium-catalyzed intramolecular alkene hydrosilylation reactions[4–6] (Scheme 1, a).[7] The strained cycloalkene norbornene (nbe) acts as a functional ligand in the Rh^I complex **4**, in conjunction with a choice of a supporting phosphine ligand (BINAP or dpph), to impact regio- and diastereoselectivity via a "hydride shuttle" process.[8] Although the proposed hydride shuttle process was intriguing, we sought to expand our initial findings into a more comprehensive understanding of the process and further enhance the regio- and diastereoselectivity. Herein, we report a cooperative functional diene and supporting phosphine ligand-mediated, highly regio- and diastereoselective Rh-catalyzed intramolecular alkene hydrosilylation and present mechanistic details concerning the diene-mediated hydride shuttle process (Scheme 1, b).



Scheme 1. Ligand-controlled rhodium-catalyzed intramolecular alkene hydrosilylation.

Results and Discussion

We envisioned that steric and electronic alteration of the metal complex by substitution of ligands, from nbe and chloride to 1,3-cyclodienes[9] and larger halides, could positively impact reactivity and selectivity. Toward this end, we devised a new rhodium complex **5**, which holds functional [1,3-cyclohexadiene (1,3-CHD)] ligand and supporting (BINAP) ligand (Scheme 2). Simultaneous incorporation of the 1,3-CHD and bromide ligands to the metal was achieved via a sequence of oxidative addition of 3-bromocyclohexene to the Rh^I dimer **6a/6b** (to **7a/7b**), β-hydride elimination (to **8a/8b**), and reductive elimination of HX (to **5**). When $[Rh(rac\text{-binap})Br]_2$ was treated with 3-bromo-

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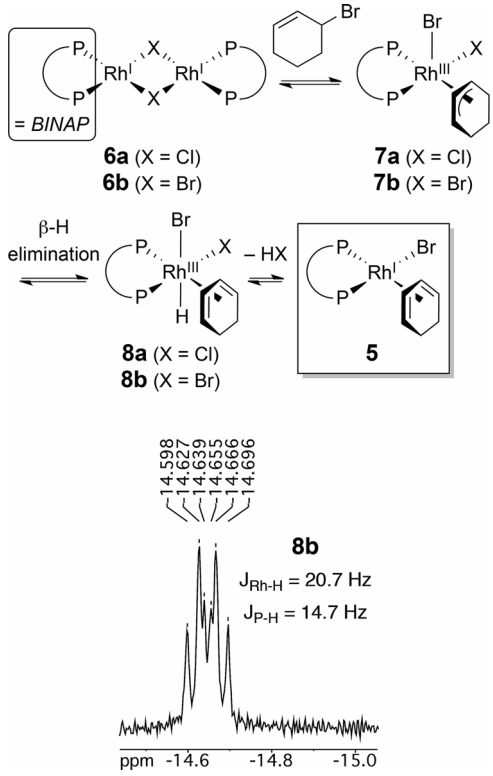
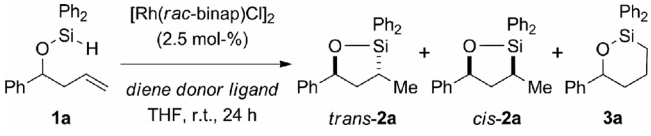
cyclohexene, the rhodium hydride intermediate **8b** and 1,3-CHD were immediately observed via ^{1}H NMR spectroscopy. The rhodium hydride signal appeared as doublet of triplets at δ = –14.7 ppm ($J_{Rh\text{-}H}$ = 20.7, $J_{P\text{-}H}$ = 14.7 Hz), indicating a *cis* orientation of the rhodium hydride in relation to the phosphine ligand.[10] We anticipated this approach would minimize the impact of competitive alkene hydrosilylation by **6a**/**6b**.



Scheme 2. Preparation of a reactive catalyst **5**.

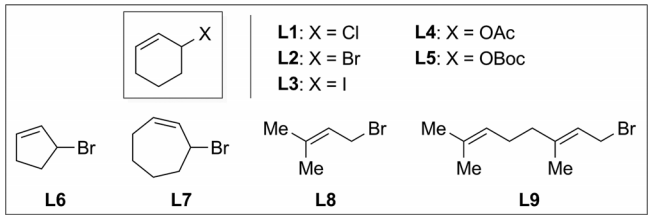
We commenced the investigation by determining whether 1,3-dienes could serve as functional ligands to improve regio- and stereoselectivity in Rh-catalyzed, intramolecular alkene hydrosilylation. As shown in Table 1, we proceeded to examine a series of cyclic "diene" donors (10 mol-%) (entries 1–9). The hydrosilylation of **1a**[11] employing [Rh(*rac*-binap)Cl]$_2$ and 3-bromocyclohexene (**L2**, entry 2) resulted in the formation of *trans*-**2a** with both excellent regio- and diastereoselectivity.[7] Chloro-, iodo-, acetate, and carbamate congeners (entries 1 and 3–5) provided significantly lower selectivities.[12] We subsequently explored the "allyl" donors [e.g. 3-(*pseudo*)halo-1-propenes], which also proved to be less selective.[13] These results demonstrate that both diene and bromide ligands are essential to achieve high levels of selectivities.[14] Other cyclic and acyclic diene donors were investigated as potential functional ligands in order to better identify characteristics thereof. 3-Bromocyclopentene **L6** and 3-bromocycloheptene **L7** provided excellent selectivities (entries 6–7, cf. entry 2). We recognized a substantial difference of reaction rates among the cyclic diene donors [**L6** ($t_{completion}$ = 1 h) > **L2** (6 h) > **L7** (> 24 h)], signifying that the hydrosilylation occurs faster when using a strained diene ligand. Acyclic diene donors (obtained from isoprenyl and geranyl bromide, **L8** and **L9**, respectively, entries 8–9) also exhibited high selectivity, albeit with diminished yields compared to their cyclic counterparts. These results support that incorporation of the functional diene ligand via β-H elimination is the key to the preparation of the active catalyst, which is responsible for amplification of both regio- and diastereoselectivity.

Table 1. Effect of functional diene ligands.[a]



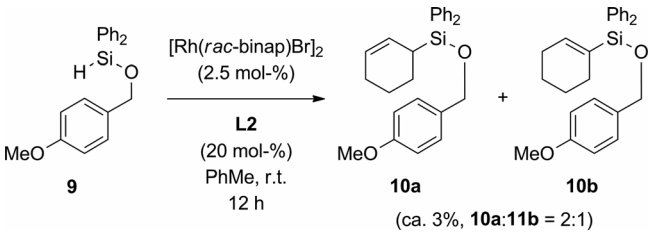
Entry	Ligand[b]	Yield [%][c]	**2a**/**3a**[d]	**2a** (*trans*/*cis*)[d]
1	L1	53	4.9:1	5.1:1
2	L2	90	24:1	> 20:1
3	L3	43	6.1:1	10.3:1
4	L4	52	4.9:1	2.6:1
5	L5	55	4.1:1	4.5:1
6	L6	90	18:1	13:1
7	L7	78	21:1	15:1
8	L8	52	8.8:1	16:1
9	L9	63	18:1	20:1

BINAP = 2,2′-bis(diphenylphosphanyl)-1,1′-binaphthyl



[a] Conditions: silane **1a** (0.1 mmol), THF (0.025 M). [b] 10 mol-% of a diene donor ligand was used. [c] Determined by ^{1}H NMR spectroscopy utilizing an internal standard (DMF). [d] Determined by GC/MS analysis and ^{1}H NMR spectroscopy.

While norbornene-mediated hydride shuttle processes have been described for Pd-catalyzed reactions, they are not well-explored in the context of Rh catalysis.[7,8] To better understand the catalytic process, the hydrosilylation of **L2** (20 mol-%) and silyl ether **9**, which does not bear an alkene moiety, was investigated (Scheme 3). Isolation of a mixture of **10a** and **10b** (ca. 3%) suggested that 1,3-CHD likely resides within a coordinative sphere of a rhodium-substrate complex.[15] Furthermore, reductive elimination at room temperature leading to **10a**/**10b** is viable within this metal



Scheme 3. Hydrosilylation of 1,3-cyclohexadiene.

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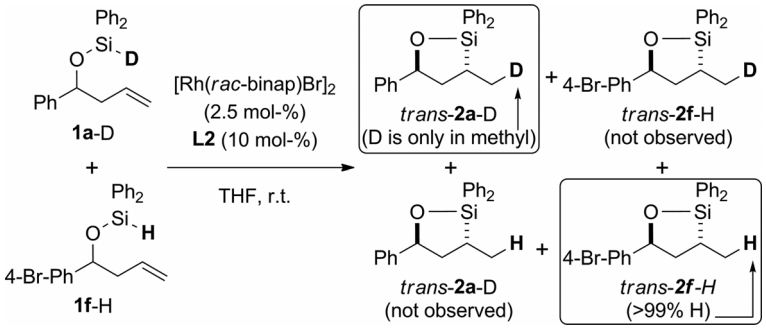


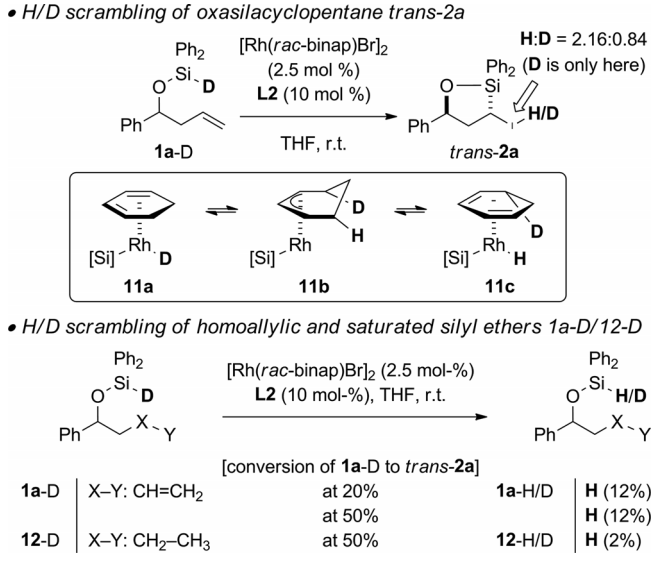
Scheme 4. Cross-over experiment.

complex when migratory insertion of a double bond is not available.[16]

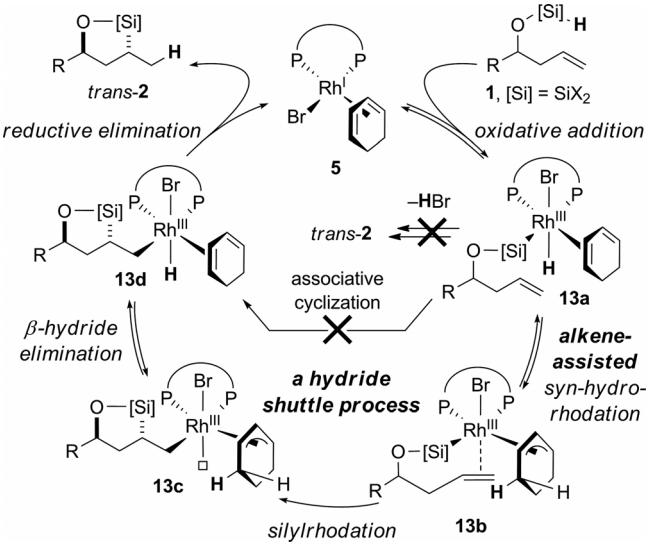
A cross-over experiment using **1a**-D and **1f**-H under the standard reaction condition confirmed that the hydrosilylation proceeds via intramolecular pathway (Scheme 4).

Further evidence of the hydride shuttle process in the hydrosilylation was obtained by the hydrogen-deuterium scrambling study with **L2** (Scheme 5, top). Both hydrogen and deuterium were incorporated at the terminal methyl group of *trans*-**2a** (the deuterium was only found in the terminal methyl position), as evidenced by an integration value of 2.16 in ^{1}H NMR spectroscopy. In addition, partially deuterated 1,3-CHD, benzene, and cyclohexene, generated by disproportionation of 1,3-CHD,[9a] were observed in GC/MS. In detail, the *syn*-migratory insertion of 1,3-CHD into Rh-D within **11a** generates **11b** having an open coordination site, which then undergoes β-H elimination to afford H/D scrambled **11c**. Of note, the reductive elimination of **11b** to give a net *cis* adduct such as **10a**/**10b** (Scheme 3) is seemingly not amenable to the presence of an alkene moiety within the substrate. This isotope-labeling study also establishes that reductive elimination to *trans*-**2a** after silyl olefin insertion (diastereoselective and putative turnover-limiting step) occurs faster than β-hydride elimination. We also studied H/D scrambling in substrate **1a**-D during the reaction (Scheme 5, bottom). When homoallylic silyl ether **1a**-D was used, fast H/D exchange (12%) in **1a**-H/D was observed at 20% conversion of **1a**-D to *trans*-**2a**. Interestingly, the H/D exchange remained constant (12%) until full consumption of **1a**-D,[17] implying that an additional H/D scrambling step would be necessary to reach the total hydrogen incorporation (16%) in *trans*-**2a**. In sharp contrast, when saturated silyl ether **12**-D was subjected to identical reaction conditions, only minor H/D exchange (ca. 2%) in **12**-H/D was observed at 50% conversion of **1a**-D. Therefore, these experiments suggest that the H/D scrambling only readily occurs in the presence of an alkene, the proximity of which would facilitate the hydrorhodation of 1,3-CHD[18] (i.e., an initiation step for a hydride shuttle process) to furnish an alkene-bound complex and subsequently undergo the C–Si bond forming cyclization.

A plausible mechanism of the diene ligand-mediated intramolecular alkene hydrosilylation is depicted in Scheme 6. Evidence suggests that 1,3-CHD functions uniquely as a catalytic vehicle; the "hydride shuttle" process exclusively renders the modified Chalk–Harrod pathway, specifically via a sequential proximal alkene-assisted *syn*-hydrorhodation,[18] silylrhodation, and β-hydride elimination (**13a**[19]



Scheme 5. H/D scrambling studies.



Scheme 6. Plausible mechanism.

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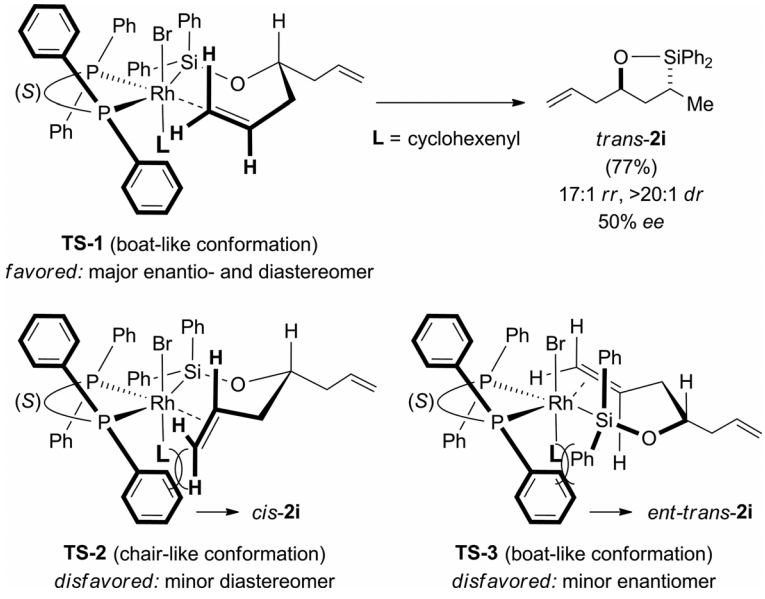
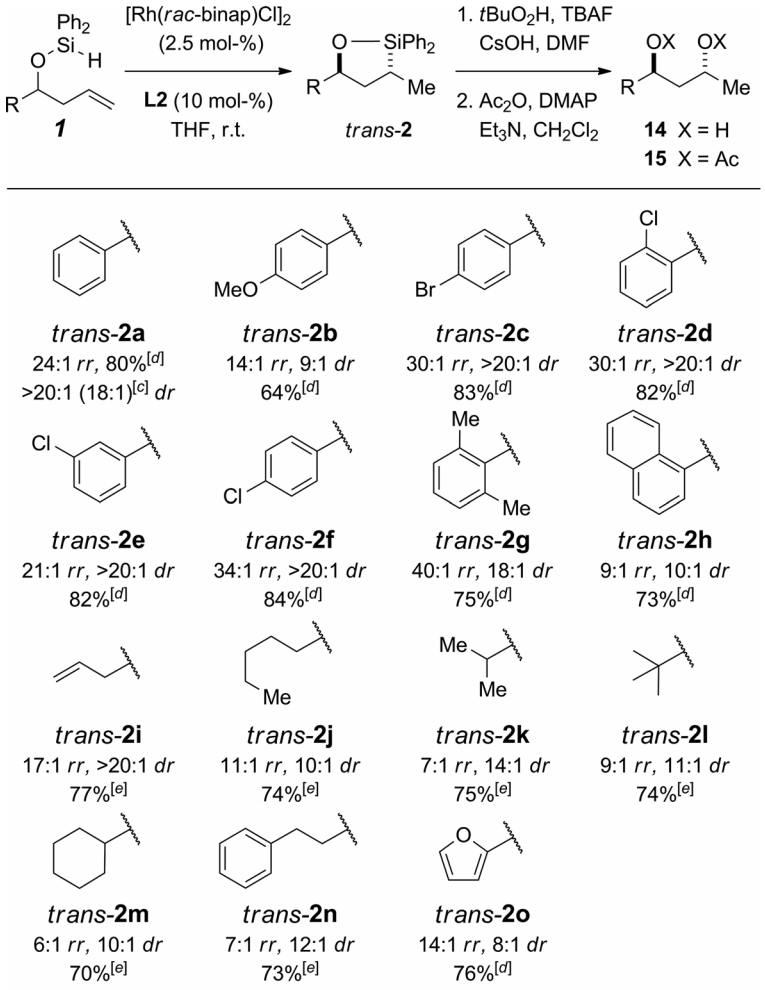


Scheme 7. Putative stereochemical model.

Table 2. Substrate scope.[a,b]



[a] Conditions: silane **1** (0.2 mmol), THF (0.025 M). [b] Regioisomeric ratio (*rr*) and diastereomeric ratio (*dr*) were determined by GC/MS analysis and ^{1}H NMR spectroscopy. [c] [Rh(*rac*-binap)Cl]$_2$ (0.5 mol-%) was used (72 h). [d] Isolated yields of diacetates **15**. [e] Isolated yields of 1,3-*anti*-diols **14**.

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to **13d**).[20–22] We speculate that the added inner-sphere steric and electronic properties of cyclohexenyl and bromide ligands within the Rh^{III} complex **13b** [the requisite intermediate for the initial H/D scrambling (**13a** to **13b**)] influence the olefin migratory insertion step (**13b** to **13c**). These effects are responsible for significant enhancement of the observed regio- and diastereoselectivity of *trans*-**2**. An additional H/D scrambling would be feasible via **13c** to **13d**. The resulting Rh^{III} hydride species **13d** then undergoes reductive elimination to provide *trans*-**2** and regenerate the Rh^{I} complex **5**.

The putative stereochemical model of the hydrosilylation is shown in Scheme 7. The boat-like conformation **TS-1** within the octahedral geometry reduces the transannular interactions between the *pseudo*-axial phenyl moiety on the silyl group and the alkene terminus, as well as a non-bonding interaction between a diphenylphosphino moiety of the ligand and the alkene terminus. Although **TS-2** adopts a chair-like conformation, it experiences the destabilizing interaction between the diphenylphosphino moiety and the *pseudo*-equatorial alkene terminus, leading to the minor diastereomer (cf. substrate-controlled hydrosilylative cyclizations typically produce *cis*-oxasilacyclopentanes, controlled by minimizing allylic strains).[4,5] We were able to determine the absolute stereochemistry when the enantioselective desymmetrizing hydrosilylation of diallylic silyl ether **1i** was carried out employing (*S*)-BINAP.[23] **TS-3** shows an interaction of the *pseudo*-equatorial phenyl moiety of the silyl group and the diphenylphosphino moiety, leading to formation of the minor enantiomer.

The utility of this reaction is enhanced by a reasonably wide substrate scope, comprised of both electronically and sterically diverse aliphatic and aromatic substrates (Table 2). Both regio- and diastereoselectivity among all substrates were greatly enhanced vis-à-vis the nbe-mediated reactions.[7] We were able to lower the catalyst loading to 0.5 mol-% without severely impacting the diastereoselectivity in *trans*-**2a** (24:1 *rr*, 18:1 *dr*); the reaction simply took longer to complete (72 h). Electron-deficient aromatic substrates (**1c**–**1f**) were more selective than the electron-rich aromatic substrate **1b**.[24] Steric hindrance was well tolerated, furnishing remarkable regio- and diastereoselectivity, as substantiated by **2g**. In particular, the regio- and diastereoselectivity of the previously challenging hetereoaromatic substrate **1o** were significantly improved (14:1 *rr*, 8:1 *dr* using 1,3-CHD vs. 4:1 *rr*, 4:1 *dr* using nbe). Oxidative desilylation of *trans*-**2**, followed by diacetylation afforded **15**.[25]

Conclusion

In summary, we have developed a cooperative ligand-mediated, Rh-catalyzed intramolecular alkene hydrosilylation to provide 1,3-*trans*-oxasilacyclopentanes (*trans*-**2**) with high regio- and diastereoselectivity. Alteration of the metal-ligand architecture employing an inner-sphere functional diene ligand (1,3-cyclohexadiene) and a supporting phosphine ligand (BINAP) permits selective access to *trans*-**2**. Notably, mechanistic details into the hydride shuttle process exploiting 1,3-cyclohexadiene as a catalytic vehicle was provided.

Experimental Section

General Procedure for Preparation of 1,3-*trans*-Oxasilacyclopentanes (*trans*-2): $[Rh(nbd)Cl]_2$ (2.3 mg, 0.005 mmol, 2.5 mol-%) and *rac*-BINAP (9.34 mg, 0.0075 mmol, 7.5 mol-%) were added to a flame-dried, septum-capped vial. The mixture was dissolved with THF (0.50 mL) and was stirred for 1 h at room temp. Volatiles including norbornadiene (nbd) were removed in vacuo (the absence of nbd was confirmed by GC/MS spectrometry), and the resulting mixture was kept under vacuum for 0.5 h. 3-Bromocyclohexene (2.3 μL, 0.020 mmol, 10 mol-%) and THF (8 mL, 0.025 M) were added to $[Rh(binap)Cl]_2$. Homoallylic silyl ether (0.2 mmol) was added in one portion to the reaction mixture via a syringe. The septum on the vial was replaced by a screw cap with a Teflon® liner, and the mixture was stirred for 24 h at room temp. The reaction progress can be monitored by GC/MS spectrometry. The yield of the reaction was determined by ^1H NMR spectroscopy by an addition of DMF (16 μL, 0.20 mmol) as an internal standard after the volatiles were removed in vacuo. The regio- and diastereomeric ratios were determined by ^1H NMR spectroscopy and GC/MS spectrometry. For an analytical purpose, the product was purified by medium pressure liquid chromatography (MPLC, hexanes/EtOAc = 80:1, 7 mL/min, retention time 10–20 min).

Supporting Information (see footnote on the first page of this article): Spectroscopic characterization data and procedures for preparation of all new compounds.

Acknowledgments

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