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# Ruthenium-Catalyzed Amination of Secondary Alcohols using Borrowing Hydrogen Methodology

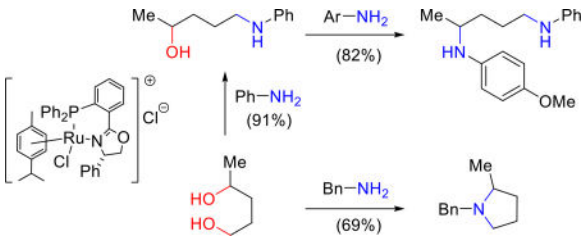
**Kostiantyn O. Marichev** and **James M. Takacs***

Department of Chemistry, University of Nebraska-Lincoln, Lincoln, Nebraska 68588-0304, United States

## Abstract

A new ruthenium complex catalyzes the amination of primary and secondary alcohols and the regioselective mono- and sequential diamination of diols via the borrowing hydrogen pathway. Several variations on new intra- and intermolecular cyclizations of aminoalcohols, diols and diamines lead to heterocyclic ring systems.

## TOC Graphic




An air stable (phosphinoxazoline)Ru(II) complex efficiently catalyzes the 1:1 alcohol:amine amination of primary and secondary alcohols, the regioselective mono- and sequential diamination of diols, and several variants of new intra- and intermolecular BH cyclizations of aminoalcohols, diols and diamines.

### Keywords

borrowing hydrogen; aminations; ruthenium(II) complex; heterocycle synthesis; hydrogen autotransfer

*Corresponding Author. jtakacs1@unl.edu.

**ASSOCIATED CONTENT**

Supporting Information

Supporting Information Available: experimental details for the synthesis and characterization of starting materials and final compounds, copies of $^{1}H$ NMR and $^{13}C$ NMR spectra of all compounds, and relevant HPLC traces. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.

## INTRODUCTION

Alcohols are widely available starting materials for synthesis but typically require stoichiometric activation for use in classical substitution reactions. The direct substitution of alcohols by amines using transition metal catalysis, specifically methodology exploiting *in situ* activation via the "borrowing hydrogen" (BH) pathway[1] (Figure 1), offers significant advantages over other substitution methods. The BH, also called hydrogen autotransfer, catalytic cycle involves initial metal-catalyzed dehydrogenation to form an intermediate carbonyl compound which undergoes addition-elimination with an amine to form the corresponding imine and water. Hydrogen generated in the dehydrogenation step reduces the imine to afford the desired alkylated amine product. Although formally a multi-step process, BH reactions are relatively "green"; they are atom efficient, carried out in one pot, and water is the sole by-product.

BH amidations[2] and aminations are typically catalyzed by ruthenium[3] or iridium[4] complexes and less commonly by other transition metal complexes.[5] The scope of ruthenium-catalyzed BH amination could be significantly improved by the development of catalyst systems that require lower catalyst loading, exhibit broader substrate scope, avoid the need for a large excess of either the alcohol or the amine and operate at more moderate temperatures and with shorter reaction times.[2] We are particularly interested in developing ruthenium catalysts that are broadly effective for the amination of secondary alcohols, an aspect that remains underdeveloped in comparison to the facile aminations of primary alcohols.

Beller and co-workers[3a–c] reported the first efficient ruthenium catalysts for the amination of secondary alcohols in a ground-breaking series of reports beginning in 2006. A prototypical secondary alcohol substrate, 1-phenylethanol, gives high yields of amine products with simple aliphatic amines using ruthenium(0) dodecacarbonyl ($Ru_3CO_{12}$) in combination with 1-phenyl-2-dicyclohexylphosphinopyrrole (6 mol% Ru, 2–5:1 alcohol:amine), but not with a simple arylamine such as aniline.[3b] Williams and co-workers reported several examples of secondary alcohol amination using 2.5 mol % dichloro(*p*-cymene)ruthenium(II) dimer and bis(2-diphenylphosphinophenyl)ether (DPEphos) ligand.[3g] The latter combination affords a quite versatile and efficient BH catalyst system. However, high conversions with simple secondary alcohols are generally achieved only under xylene reflux conditions for (5 mol% Ru, 150 °C, 24 h). In the present work, the air-stable ruthenium(II) complex **1** was found to promote high conversion of both aliphatic and aromatic amines with 1-phenylethanol (and a variety of more complex alcohols) using 2.0% or lower catalyst loading and a 1:1 ratio of alcohol to amine.

## RESULTS AND DISCUSSION

Complex **1** was among a series of ruthenium complexes prepared from dichloro(*p*-cymene)ruthenium(II) dimer and a small but quite varied set of chelating and non-chelating ligand systems (Figure 2). Our study was intended to quickly assay how factors such as sterics, electronics, neutral versus anionic ligands, neutral versus cationic catalyst precursors, and coordinating versus non-coordinating counterions affect the outcome in a series of model reactions of secondary alcohols with primary amines. In addition to the

phosphinooxazoline[6a] complex **1**, complexes incorporating bisoxazoline,[6b] TADDOL-derived phosphite,[6c,d] bipyridine,[6e] and IMes-NHC[6f] ligands were prepared. Complexes **3**,[6e] **7**,[6g] and **9**[6f] are known; however, their use for the amination of secondary alcohols has to the best of our knowledge not been reported. The simple chiral ligands were included in our study to evaluate the potential for asymmetric induction, although in no case was significant induction realized.

After arriving at a suitable set of initial reaction conditions, complexes **1–9** were individually screened in model reactions combining a secondary benzylic or non-benzylic alcohol (i.e., 1-phenylethanol and 2-octanol) with an aliphatic or aromatic amine (i.e., *n*-hexylamine and aniline); products **10a–d** are formed (Figure 3). Cationic complexes with coordinated ligands that are not readily deprotonated (e.g., **1–4**) generally afford more efficient catalysts. Several complexes (e.g., **3**) work well in some reactions but not others, while others (e.g., **7**) proved surprisingly poor under the reaction conditions used. Complex **1** gives yields in the range of 72–88% for the four substrate combinations. It is the overall most efficient catalyst precursor and therefore selected for further study.

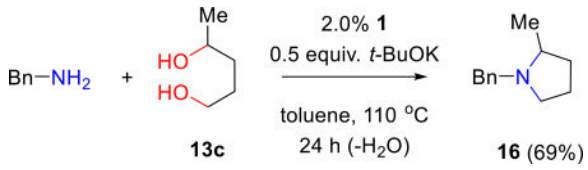
The reactivity of cationic complexes led us to study analogues of **1** in which one or two chlorides were replaced by more weakly coordinating counter-anions via silver-mediated exchange (i.e., complexes **1'a–d** and **1"a–d**, respectively) (Figure 4). Complexes **1'a–d** were generally more effective than the corresponding complexes **1"a–d** but none of the anion-exchanged catalysts are as effective as complex **1**. Complexes in which chloride is exchanged for triflate or trifluoroacetate are found to be particularly ineffective catalyst precursors.

Complex **1** is applicable to representative examples for a wide variety of the common applications of BH for amine synthesis, including aminations of a variety of primary and secondary alcohols, some diols, and several intra- and intermolecular cyclizations of secondary aminoalcohols, amines and diols. For example, complex **1** catalyzes the amination of secondary alcohols **11a–c** with aniline, benzylamine, and *n*-hexylamine (Figure 5). Products **12a–f** are obtained in good yields without using an excess of either the amine or alcohol (1:1 ratio used).

Primary alcohols also undergo efficient amination with complex **1**. Their reactions are significantly faster as illustrated by the regioselective aminations of 1,2-propanediol (**13a**), 1,3-butanediol (**13b**) and 1,4-pentanediol (**13c**) by one equivalent of aniline or benzylamine. The corresponding aminoalcohols **14** were obtained in high yields and with excellent regioselectivity (Figure 6); 1.0% of complex **1** is sufficient for efficient conversion. Beller and co-workers had previously reported the regioselective amination of 1-phenyl-1,2-ethanediol [(2 mol % $Ru_3CO_{12}$ and *N*-phenyl-2-(dicyclohexyl-phosphanyl)pyrrole (CataCXium PCy)], although the maximum yield reported with aniline was 55%.[7] Similarly, Oe reported the regioselective amination of 1-phenyl-1,2-ethanediol with secondary amines (5 mol% Ru and (*S,R*)-Josiphos).[8]

The isolated aminoalcohols **14a, 14b**, and **14e** are subsequently used to synthesize diamines **15a–f** by reaction of the secondary alcohol. It is again noteworthy that the second amination

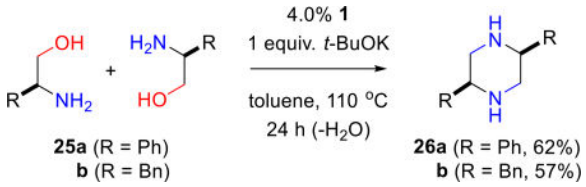
is successful for both aliphatic and aromatic amines. Furthermore, the data illustrate that moderate electron withdrawing or donating substituents in the arylamine reactant are well tolerated. The formation of simple nitrogen heterocycles from the condensation of diols with amines via BH is well-precedented. We find the 1:1 reaction of benzylamine with 1,4-pentanediol (**13c**) leads to the formation of *N*-benzyl-2-methylpyrrolidine (**16**) in good yield (69%).




(1)

Figure 7 shows other examples of five- and six-membered heterocycle formation via BH cyclizations of aminoalcohols **17**.[9] Appropriately substituted derivatives of **17a** cyclize to 2,4,4-trisubstituted pyrrolidines **18** and **19** and to the 2,5-disubstituted pyrrolidine **20**; the latter, isolated as its sulphonamide derivative, is produced as a 4:1 mixture of *cis*- to *trans*-diastereomers. 2-Phenylindole (**21**) is produced in excellent yield (94%) from its aminoalcohol precursor; however, likely due to its aromaticity, the BH reaction stops at the indole stage rather than undergoing further reduction. The formation of indoles from primary and secondary aminoalcohols has previously been reported via iridium-catalyzed BH methodology.[4a] Our report here is to the best of our knowledge the first complementary example using a ruthenium catalyst. Other multicomponent dehydrogenative condensations leading to aromatic nitrogen heterocycles (e.g., pyrroles, pyridines and pyrimidines) have been reported by Kempe,[10] Milstein[11] and Beller.[12] Complex **1** also affords six-membered ring saturated heterocycles, i.e., 2-methylmorpholine (**22**) and dihydrobenzoxazine derivatives **23** and **24**, from appropriately substituted aminoalcohols possessing the core structure illustrated by **17b**.

Chiral piperazines are useful building blocks for the total synthesis of biologically active compounds[13] and have been used in the design of flexible ligands for self-assembled coordination polymers.[14] The iridium-catalyzed cyclodimerization of ethanolamine derivatives was reported by Yamaguchi and co-workers.[15] We report what we believe are the first examples in which ruthenium-catalyzed BH methodology is used to cyclodimerize readily available chiral aminoalcohols. (*S*)-Phenylglycinol (**25a**) and (*S*)-phenylalaninol (**25b**) dimerize to give chiral *cis*-2,5-disubstituted piperazines in good yield (eq 2). We see no evidence for epimerization at the stereocenter alpha to nitrogen during the course of reaction; piperazines **26a** and **26b** are essentially single enantiomers as judged by chiral HPLC analysis.




(2)

The cross-coupling of diamines with diols provides another route to piperazines (Figure 8). Iridium-catalyzed cyclocondensations of vicinal diamines with vicinal diols was reported by Madsen and co-workers.[16] While it may be possible to further optimize the reaction conditions, BH cyclization using complex **1** using the standard conditions is thus far only moderately efficient; 2-methylpiperazine (**28**) and tetrahydroquinoxaline **29** are obtained in ca. 40% yield from the reaction of 1,2-propanediol (**13a**) with the requisite diamine. In contrast, the reaction of 1,4-pentanediol (**13c**) 1,2-phenylenediamine forms the 8-membered ring in 1,2,3,4-tetrahydrobenzo[b][1,4]diazocine derivative **30** in much higher yield (78%). However, the BH cyclodimerization stops short of producing the fully reduced product.

## CONCLUSION

In summary, ruthenium(II) complex **1** efficiently catalyzes the BH amination of a variety of primary and secondary alcohols with alkyl and aryl amines, including the regioselective mono- and sequential diamination of diols. Several variants of intra- and intermolecular BH cyclizations of aminoalcohols, diols and diamines are also demonstrated. The latter lead to five- and six-membered ring heterocycles and in one case an eight-membered ring heterocycle.

## EXPERIMENTAL SECTION

NMR spectra were recorded on 300 MHz or 700 MHz Bruker Avance III HD NMR spectrometers using residue $CDCl_3$ (δ 7.26 ppm) or $H_2O$ (d 1.56 ppm) for $^1H$ NMR reference. The central $CDCl_3$ resonance (δ 77.16 ppm) is used as the $^{13}C$ NMR reference. $^1H$ NMR spectra are reported as follows (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, m = unresolved multiplet). Chiral HPLC analyses were performed on an ISCO model 2360 HPLC with Daicel chemical industries, LTD. Chiralcel OJH and Chiralpak AD or IC columns (0.46 × 25 cm). Data were recorded and analyzed with ChromPerfect chromatography software (version 5.1.0). IR spectra were recorded using an Avatar 360 FT-IR. Optical rotations were measured as solutions in dichloromethane or chloroform, and recorded using an Autopol III automatic polarimeter; the concentration, *c*, is reported in g/100 mL.

### Chloro(*p*-cymene)[(*S*)-2-(2-(diphenylphosphanyl)-phenyl)-4-phenyl-4,5-dihydrooxazole]ruthenium(II) chloride (1)

A mixture of dichloro(p-cymene)-ruthenium(II) dimer 61 mg (0.10 mmol), (*S*)-2-(2-(diphenylphosphanyl)phenyl)-4-phenyl-4,5-dihydrooxazole 81 mg (0.20 mmol) in 10 mL of

methanol was stirred at room temperature for 3 h. The solvent was evaporated. Flash chromatography on silica gel affords the ruthenium(II) complex **1** (128 mg, 90%) as orange solid: mp 116–118 °C; $R_f$ = 0.4 (dichloromethane/methanol 9:1); $[\alpha]_D^{25}$ = +183.8 (*c* 0.67, $CH_2Cl_2$); $^1$H NMR (700 MHz, $CDCl_3$) δ 8.15 (dd, *J* = 9.8, 4.2 Hz, 1H), 7.77 (dd, *J* = 10.5, 7.7 Hz, 2H), 7.62-7.54 (m, 12H), 7.48-7.42 (m, 2H), 7.38-7.35 (m, 2H), 6.31 (dd, *J* = 7.0, 3.5 Hz, 2H), 5.70 (t, *J* = 4.9 Hz, 1H), 5.56 (d, *J* = 6.3 Hz, 1H), 4.95 (t, *J* = 9.8 Hz, 1H), 4.61 (dd, *J* = 9.1, 4.2 Hz, 1H), 4.44 (d, *J* = 6.3 Hz, 1H), 2.67 (septet, *J* = 6.3 Hz, 1H), 1.17 (d, *J* = 7.0 Hz, 3H), 1.08 (s, 3H), 0.80 (d, *J* = 7.0 Hz, 3H) ppm; $^{13}$C NMR (175 MHz, $CDCl_3$) δ 167.8 (d, *J* = 5.3 Hz), 139.4, 134.0, 133.9, 133.4, 133.3, 132.1, 131.7, 131.5, 129.5, 129.4, 129.3, 128.9, 128.8, 127.6, 76.6, 76.0, 31.0, 22.7, 20.1, 16.8 ppm; $^{31}$P NMR (283.4 MHz, $CDCl_3$) δ 34.8 ppm; IR (neat) 3366, 3052, 2160, 2031, 1599, 1434, 1093, 729, 696 $cm^{-1}$; HRMS (ESI) calcd. for $C_{37}H_{36}NOP^{35}Cl^{96}Ru$ [(M-Cl)$^+$], 672.1299; found, 672.1306 *m/z*.

### Sample Procedure for the Reaction of a Secondary Alcohol: *N*-(1-Phenylethyl)hexan-1-amine (10a).[3b,4f,5c,17]

In a nitrogen-filled glovebox an 8 mL oven-dried sample vial was charged with a ruthenium(II) complex **1** (7.1 mg, 0.01 mmol, 2 mol %), 1-phenylethanol (61 mg, 0.50 mmol), *n*-hexylamine (51 mg, 0.50 mmol), and potassium *tert*-butoxide (28 mg, 0.25 mmol). Toluene (1 mL) was added and the vial sealed with a teflon-lined septum/screw cap. The reaction mixture was taken outside the glovebox and heated to 110 °C for 24 h after which the mixture was cooled to room temperature. Water (5 mL) was added and the mixture extracted with ethyl acetate (3 × 5 mL). The combined organics were dried (anhyd $Na_2SO_4$), and the solvent was removed under vacuum. Purification by flash chromatography on silica gel afforded compound **10a** (73 mg, 71%) as pale yellow liquid: $R_f$ = 0.4 (hexanes/dichloromethane 1:1); $^1$H NMR (300 MHz, $CDCl_3$) δ 7.35-7.30 (m, 4H), 7.28-7.23 (m, 1H), 7.20 (s, 2H), 3.78 (q, *J* = 6.6 Hz, 1H), 2.56-2.40 (m, 2H), 1.61 (br s, 1H), 1.54-1.43 (m, 2H), 1.38 (d, *J* = 6.6 Hz, 3H), 1.34-1.24 (m, 6H), 0.89 (t, *J* = 6.6 Hz, 3H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 145.9, 128.4, 126.8, 126.6, 58.4, 47.9, 31.8, 30.3, 27.1, 24.3, 22.6, 14.1 ppm.

### Sample Procedure for the Reaction of a Primary Alcohol: *N*-(1-(benzyloxy)propan-2-yl)aniline (12a)

To a nitrogen-flushed flask equipped with reflux condenser was added **1** (25.7 mg, 0.036 mmol), 1-(benzyloxy)propan-2-ol **11a** (300 mg, 1.80 mmol), aniline (168 mg, 1.80 mmol) and potassium *tert*-butoxide (101 mg, 0.90 mmol). Toluene (4 mL) was added, and the resulting reaction mixture was heated and stirred (110 °C, 24 h). Afterwards, the mixture was cooled (RT) and partitioned with water (8 mL). The aqueous layer was extracted with ethyl acetate (2 × 5 mL) and the combined organic layers dried (anhyd. $Na_2SO_4$), filtered and concentrated. Flash chromatography on silica gel afforded **12a** (200 mg, 46%) as a light colored liquid: $R_f$ = 0.45 (hexanes/dichloromethane 1:2); $^1$H NMR (300 MHz, $CDCl_3$) δ 7.39-7.31 (m, 5H), 7.19 (dd, *J* = 8.4, *J* = 7.5 Hz, 2H), 6.75 (t, *J* = 7.2 Hz, 1H), 6.63 (d, *J* = 7.8 Hz, 2H), 4.58 (s, 2H), 3.81 (br s, 1H), 3.78-3.68 (m, 1H), 3.60-3.48 (m, 2H), 1.29 (d, *J* = 6.3 Hz, 3H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 147.4, 138.3, 129.3, 128.4, 127.7, 127.6, 117.3, 113.5, 73.5, 73.3, 48.4, 18.1 ppm; IR (neat) 2860, 2160, 2020, 1601, 1503, 1453,

1315, 1257, 1074, 745, 695 $cm^{-1}$; HRMS (ESI) calcd. for $C_{16}H_{19}NONa$ [$(M+Na)^+$], 264.1364; found, 264.1354 *m/z*.

### Procedure for the Reaction of a Diol: (Phenylamino)propan-2-ol (14a).[18]

To a nitrogen-flushed flask equipped with reflux condenser was added **1** (21.4 mg, 0.030 mmol), 1,2-propanediol (228 mg, 3.00 mmol), aniline (279 mg, 3.00 mmol) and potassium *tert*-butoxide (168 mg, 1.50 mmol). Toluene (5 mL) was added, and the resulting reaction mixture was heated and stirred (110 °C, 24 h). Afterwards, the mixture was cooled (RT) and partitioned with water (10 mL). The aqueous layer was extracted with ethyl acetate (2 × 10 mL) and the combined organic layers dried (anhyd $Na_2SO_4$), filtered, and concentrated. Flash chromatography on silica gel affords aminoalcohol **14a** (399 mg, 88%) as an amber liquid: $R_f$ = 0.5 (ethyl acetate/hexanes 1:1); $^1H$ NMR (300 MHz, $CDCl_3$) δ 7.22 (t, *J* = 8.1 Hz, 2H), 6.77 (t, *J* = 7.2 Hz, 1H), 6.68 (d, *J* = 7.8 Hz, 2H), 4.09-3.99 (m, 1H), 3.25 (dd, *J* = 12.9, 3.3 Hz, 1H), 3.01 (dd, *J* = 12.9, 8.7 Hz, 1H overlapping with br s, 2H), 1.28 (d, *J* = 6.0 Hz, 3H) ppm; $^{13}C$ NMR (75.5 MHz, $CDCl_3$) δ 148.3, 129.3, 117.9, 113.3, 66.4, 51.7, 20.9 ppm.

### *N*$^4$-(4-Methoxyphenyl)-*N*$^1$-phenylpentane-1,4-diamine (15e)

The general procedure (2 mol % **1**) gave **15e** (186 mg, 82%) as a pale amber oil: $R_f$ = 0.4 (ethyl acetate/hexanes 1:2); $^1H$ NMR (300 MHz, $CDCl_3$) δ 7.21 (dd, *J* = 8.4, 7.2 Hz, 2H), 6.82 (dd, *J* = 6.6, 2.4 Hz, 2H), 6.73 (t, *J* = 7.2 Hz, 1H), 6.64-6.57 (m, 4H), 3.79 (s, 3H), 3.47 (tq, *J* = 6.0 Hz, 1H overlapping with br s, 2H), 3.16 (t, *J* = 6.6 Hz, 2H), 1.81-1.54 (m, 4H), 1.21 (d, *J* = 6.3 Hz, 3H) ppm; $^{13}C$ NMR (75.5 MHz, $CDCl_3$) δ 152.0, 148.4, 141.7, 129.3, 117.2, 115.0, 114.8, 112.7, 55.9, 49.4, 44.0, 34.7, 26.1, 21.0 ppm; IR (neat) 3385, 2960, 2844, 2024, 1605, 1518, 1312, 1305, 1231, 1034, 821, 751, 691 $cm^{-1}$; HRMS (ESI) calcd. for $C_{18}H_{24}N_2ONa$ [$(M+Na)^+$], 307.1786; found, 307.1793 *m/z*; calcd. for $C_{18}H_{25}N_2O$ [$(M+H)^+$], 285.1967; found, 285.1965 *m/z*.

### 1-Benzyl-2-methylpyrrolidine (16).[19a,b]

The general procedure (2 mol % **1**) gave **16** (145 mg, 69%) as a pale yellow oil: $R_f$ = 0.3 (dichloromethane/methanol 4:1); $^1H$ NMR (300 MHz, $CDCl_3$) δ 7.39-7.25 (m, 5H), 4.06 (d, *J* = 12.6 Hz, 1H), 3.18 (d, *J* = 12.9 Hz, 1H), 2.94 (td, *J* = 9.9, 2.7 Hz, 1H), 2.41 (tq, *J* = 7.2 Hz, 1H), 2.14 (q, *J* = 9.0 Hz, 1H), 2.00-1.92 (m, 1H), 1.76-1.63 (m, 2H), 1.56-1.47 (m, 1H), 1.22 (d, *J* = 6.0 Hz, 3H) ppm; $^{13}C$ NMR (75.5 MHz, $CDCl_3$) δ 139.6, 129.1, 128.2, 126.8, 59.6, 58.4, 32.8, 21.5, 19.2 ppm; HRMS (ESI) calcd. for $C_{12}H_{18}N$ [$(M+H)^+$], 176.1440; found, 176.1431 *m/z*.

### General Procedure for the BH Cyclization of Aminoalcohols 17a/b: 2,4,4-Triphenylpyrrolidine (19)

To a nitrogen-flushed flask equipped with reflux condenser was added **1** (14.3 mg, 0.020 mmol), the appropriate secondary aminoalcohol (1.00 mmol) and potassium *tert*-butoxide (56.0 mg, 0.500 mmol). Toluene (3 mL) was added, and the resulting reaction mixture was heated and stirred (110 °C, 24 h). Afterwards, the mixture was cooled (RT) and partitioned with water (5 mL). The aqueous layer was extracted with ethyl acetate (2 × 5 mL), and the

combined organic layers were dried (anhyd $Na_2SO_4$), filtered, and concentrated. Flash chromatography on silica gel affords **19** (218 mg, 73%) as a pale yellow oil: $R_f$ = 0.45 (ethyl acetate); $^1$H NMR (300 MHz, $CDCl_3$) δ 7.43-7.16 (m, 15H), 4.35 (dd, *J* = 10.2, 6.9 Hz, 1H), 3.99 (dd, *J* = 11.1, 1.5 Hz, 1H), 3.63 (d, *J* = 11.1 Hz, 1H), 3.07 (ddd, *J* = 12.6, 6.6, 1.5 Hz, 1H), 2.46 (dd, *J* = 12.6, 10.2 Hz, 1H), 1.81 (br s, 1H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 147.4, 146.4, 143.9, 128.6, 128.5, 128.3, 127.1, 127.0, 126.9, 126.4, 126.2, 126.1, 61.1, 58.4, 57.0, 48.0 ppm; IR (neat) 3807, 2926, 1493, 1445, 1032, 910, 752, 697 $cm^{-1}$; HRMS (ESI) calcd. for $C_{22}H_{22}N$ [$(M+H)^+$], 300.1752; found, 300.1738 *m/z*.

### 3-Methyl-3,4-dihydro-2*H*-benzo[b][1,4]oxazine (23)[20a,b]

The general procedure (2 mol % **1**) gave **23** (137 mg, 92%) as a pale yellow oil: $R_f$ = 0.4 (ethyl acetate/hexanes 1:3); $^1$H NMR (300 MHz, $CDCl_3$) δ 6.83-6.75 (m, 2H), 6.71-6.60 (m, 2H), 4.21 (dd, *J* = 10.5, 2.7 Hz, 1H), 3.80 (dd, *J* = 10.5, 8.1 Hz, 1H), 3.69 (br s, 1H), 3.62-3.51 (m, 1H), 1.21 (d, *J* = 6.3 Hz, 3H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 143.6, 133.4, 121.3, 118.8, 116.5, 115.4, 70.7, 45.2, 17.8 ppm.

### General Procedure for the BH Self-Dimerization of Chiral Aminoalcohols: (2*S*,5*S*)-2,5-Diphenyl-piperazine (26a)

A condenser equipped flask with a mixture of **1** (57.0 mg, 0.080 mmol), chiral aminoalcohol (2.00 mmol) and potassium *tert*-butoxide (224 mg, 2.00 mmol) was degassed and flushed with nitrogen. Toluene (5 mL) was added, and the reaction mixture was stirred at 110 °C for 24 h. The reaction mixture was cooled (RT) and DCM (8 mL) added. The resulting suspension was filtered through celite, and the solvents evaporated. Flash chromatography on silica gel afforded **26a** (148 mg, 62%) as a yellow oil: $R_f$ = 0.35 (methanol); $[\alpha]_D^{25}$ = +54.6 (*c* 1.0, $CHCl_3$); $^1$H NMR (300 MHz, $CDCl_3$) δ 7.42-7.26 (m, 10H), 4.00 (dd, *J* = 12.6, 10.8 Hz, 2H), 3.27 (dd, *J* = 12.6, 7.2 Hz, 2H), 3.14 (dd, *J* = 12.6, 8.1 Hz, 2H), 2.12 (br s, 2H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 142.8, 128.2, 127.6, 127.0, 57.8, 49.1 ppm; IR (neat) 3323, 3019, 2701, 1460 $cm^{-1}$; HRMS (EI) calcd. for $C_{16}H_{18}N_2$ [$M^+$], 238.1470; found, 238.1476 *m/z*.

### General Procedure for BH Condensation of Diamines with Diols: 5-Methyl-1,2,3,4-tetrahydrobenzo[b][1,4]-diazocine (30)

A condenser equipped flask with a mixture of **1** (34.3 mg, 0.048 mmol), diol (1.20 mmol), diamine (1.20 mmol) and potassium *tert*-butoxide (135 mg, 1.20 mmol) was degassed and flushed with nitrogen. Toluene (4 mL) was added, and the reaction mixture was stirred at 110 °C for 24 h. After cooling (RT), DCM (5 mL) was added, and the resulting suspension was filtered through celite. Flash chromatography on silica gel afforded **30** (163 mg, 78%) as a sticky brown oil: $R_f$ = 0.3 (ethyl acetate/hexanes 1:2); $^1$H NMR (300 MHz, $CDCl_3$) δ 6.75-6.69 (m, 2H), 6.63-6.55 (m, 2H), 3.50-3.41 (m, 1H), 3.25-3.17 (m, 1H), 1.94-1.78 (m, 4H), 1.49 (s, 3H) ppm; $^{13}$C NMR (75.5 MHz, $CDCl_3$) δ 144.4, 141.2, 121.1, 120.3, 112.0, 109.5, 88.8, 54.4, 39.5, 28.7, 24.5 ppm; IR (neat) 2961, 2872, 1585, 1487, 1295, 1232, 718 $cm^{-1}$; HRMS (EI) calcd. for $C_{11}H_{14}N_2$ [$M^+$], 174.1157; found, 174.1164 *m/z*.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

## Acknowledgments

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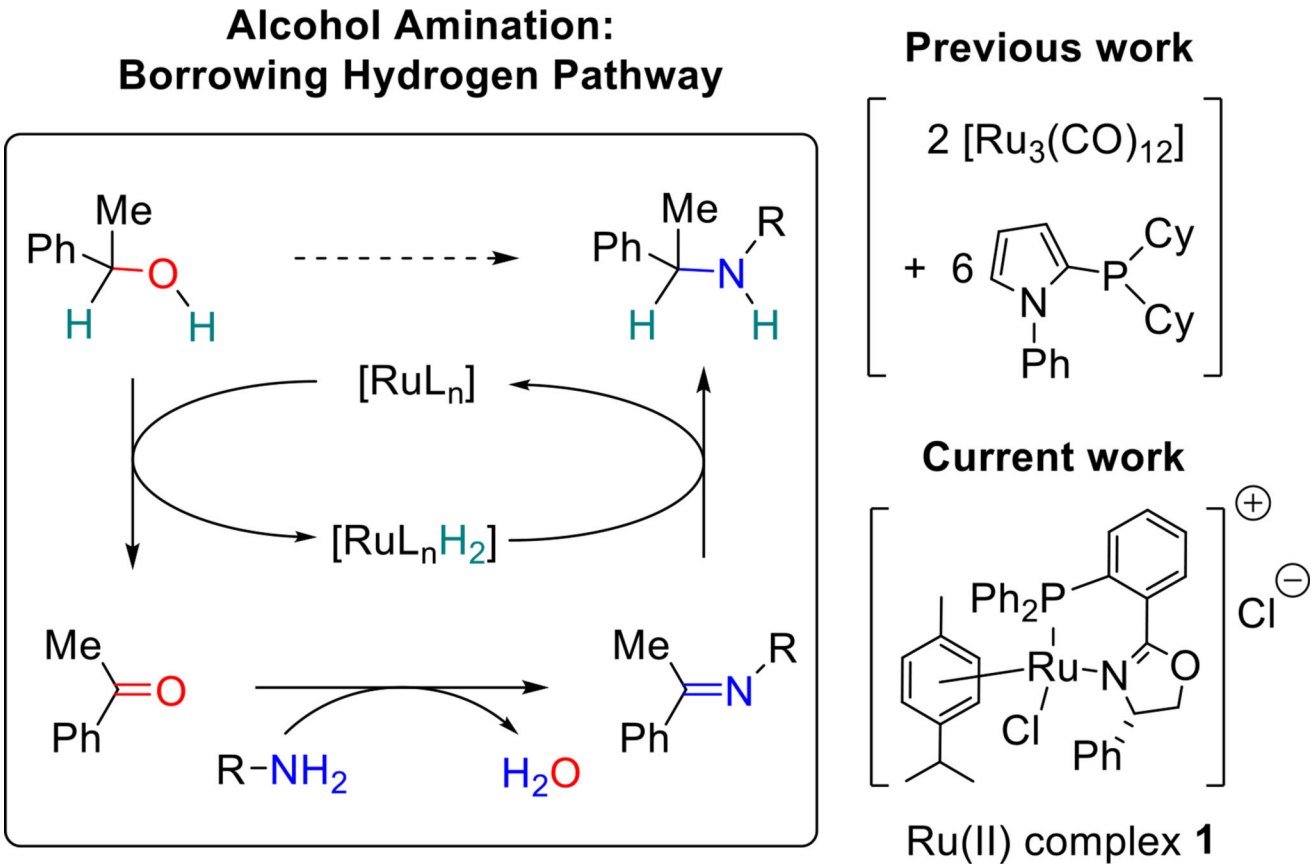


**Figure 1.**
Ruthenium-catalyzed amination of 1-phenylethanol via the BH method.

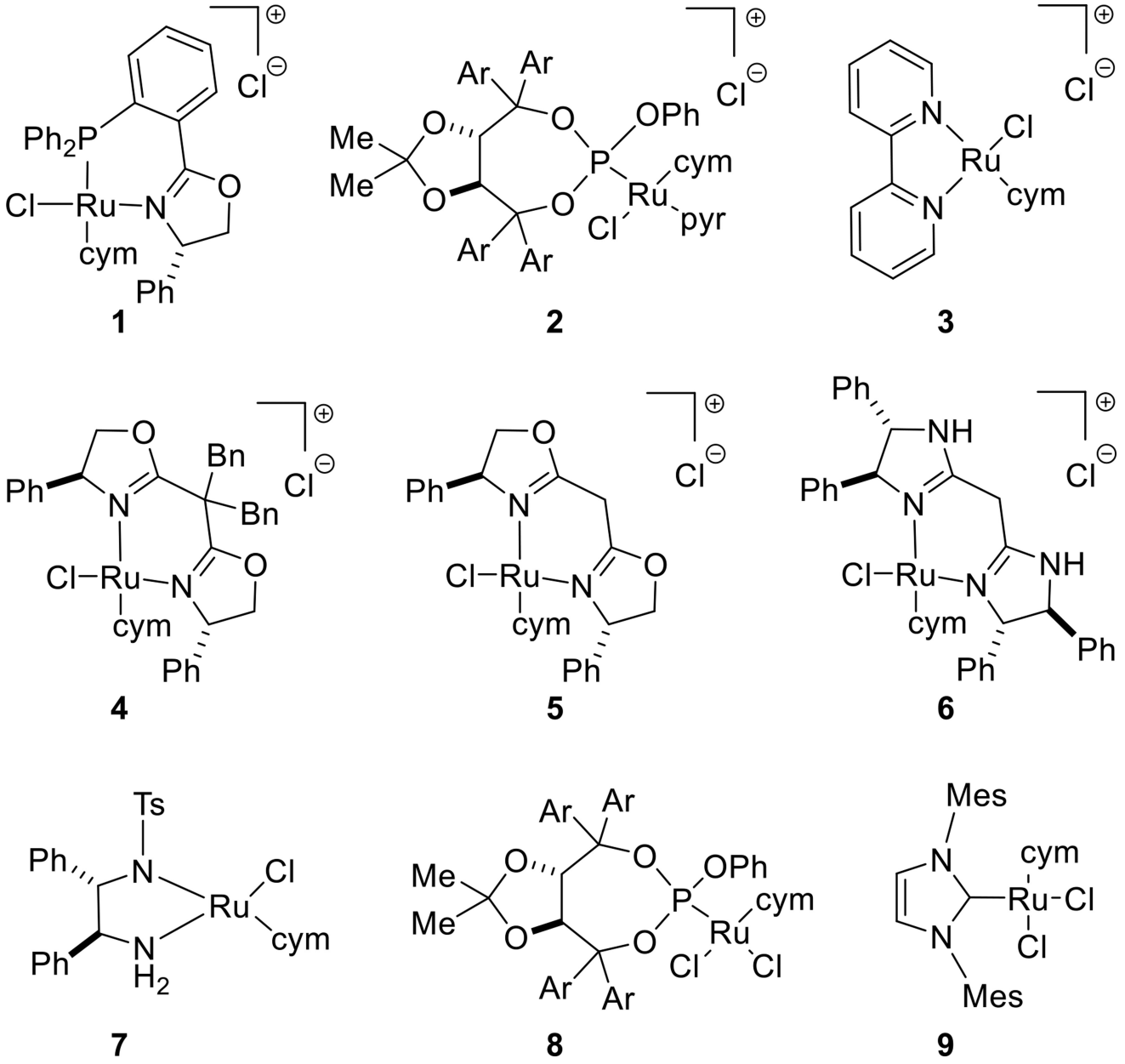


**Figure 2.**

Ru(II) complexes **1–9** incorporate chelating and non-chelating ligand systems (cym = *p*-cymene; pyr = pyridine; Ar = 3,5-dimethylphenyl).

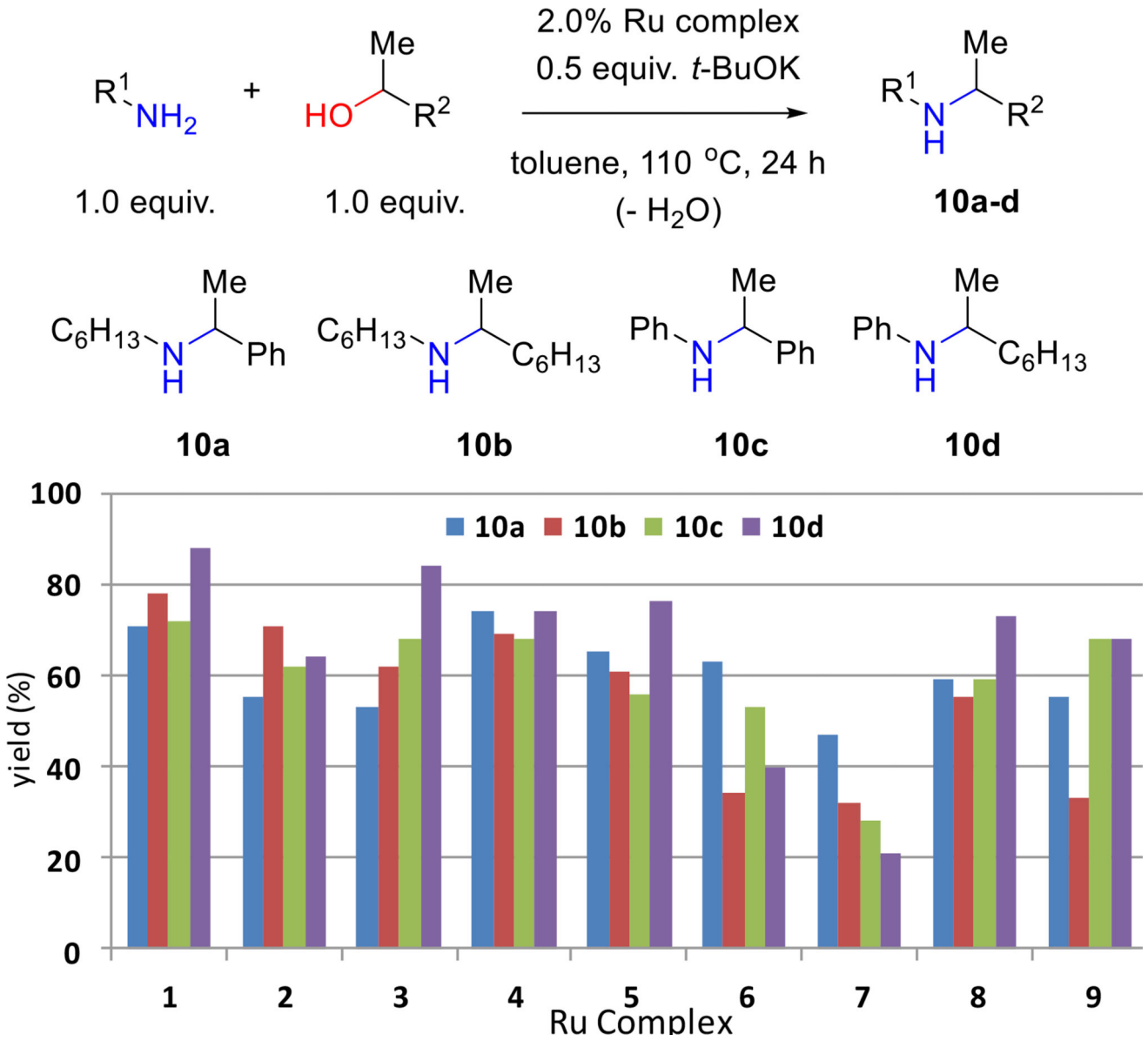


**Figure 3.**

Use of complexes **1–9** for the preparation of amines **10a–d**; yields are the average of two runs on the scale of 0.6 mmol each of amine and alcohol.

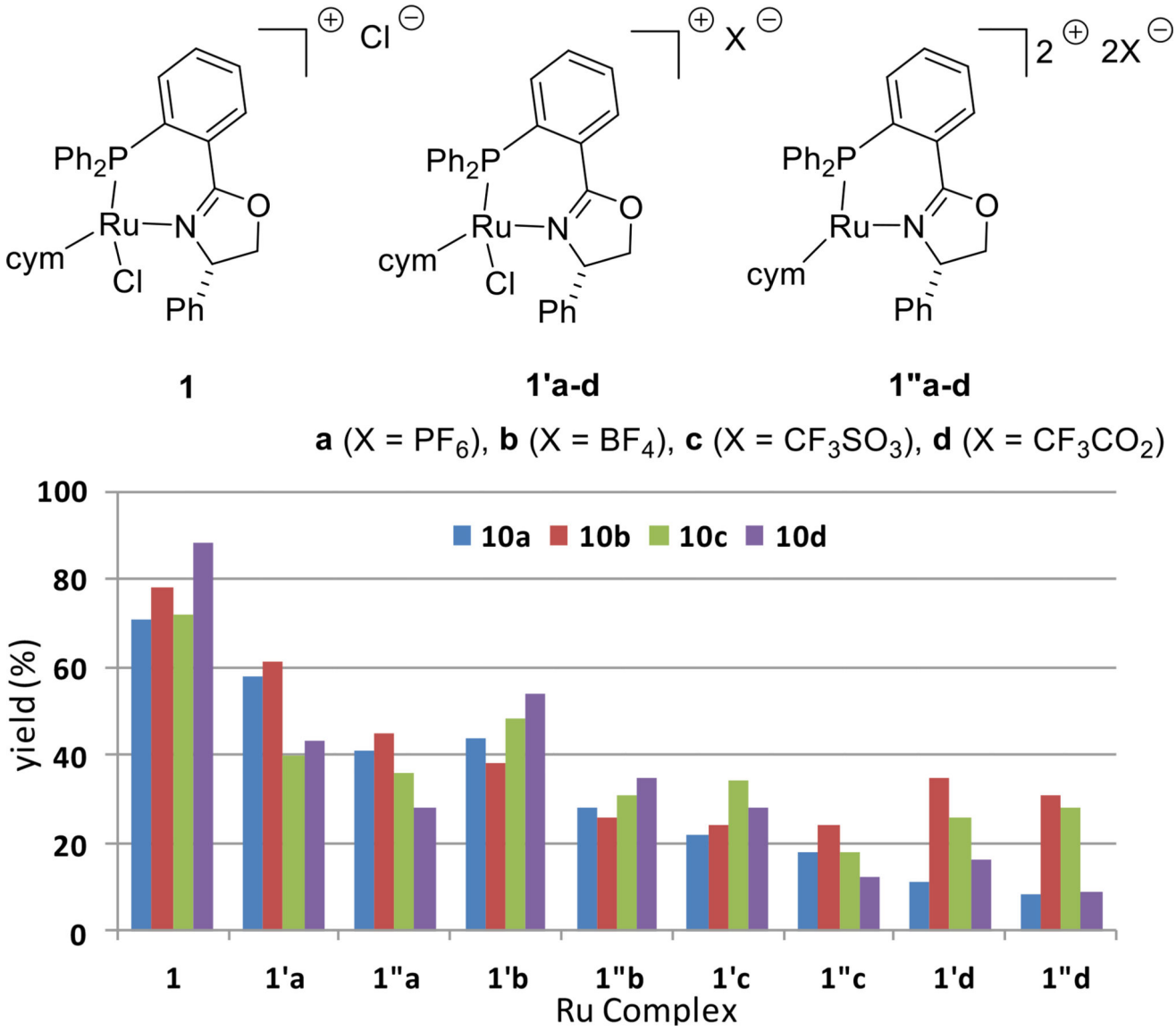


**Figure 4.**
The effect of exchanging counteranion on the percent yield of **10a–d**.

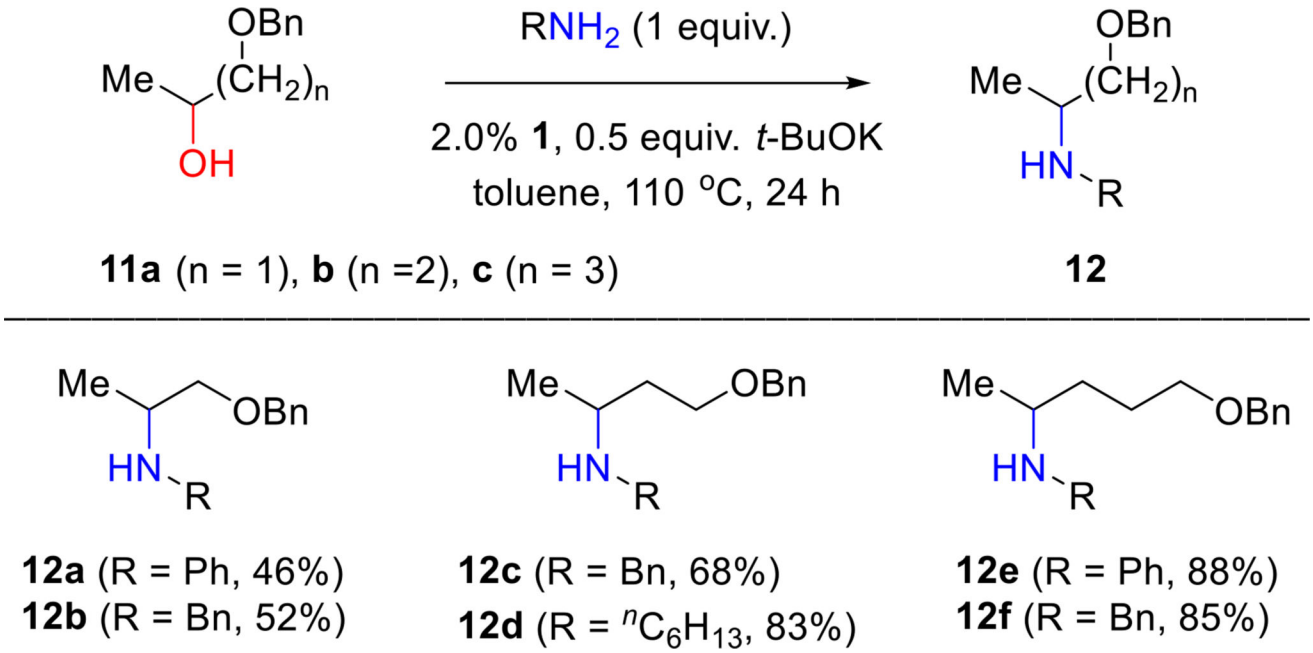


**Figure 5.**
Aminations of secondary alcohols **11a–c** using complex **1**.

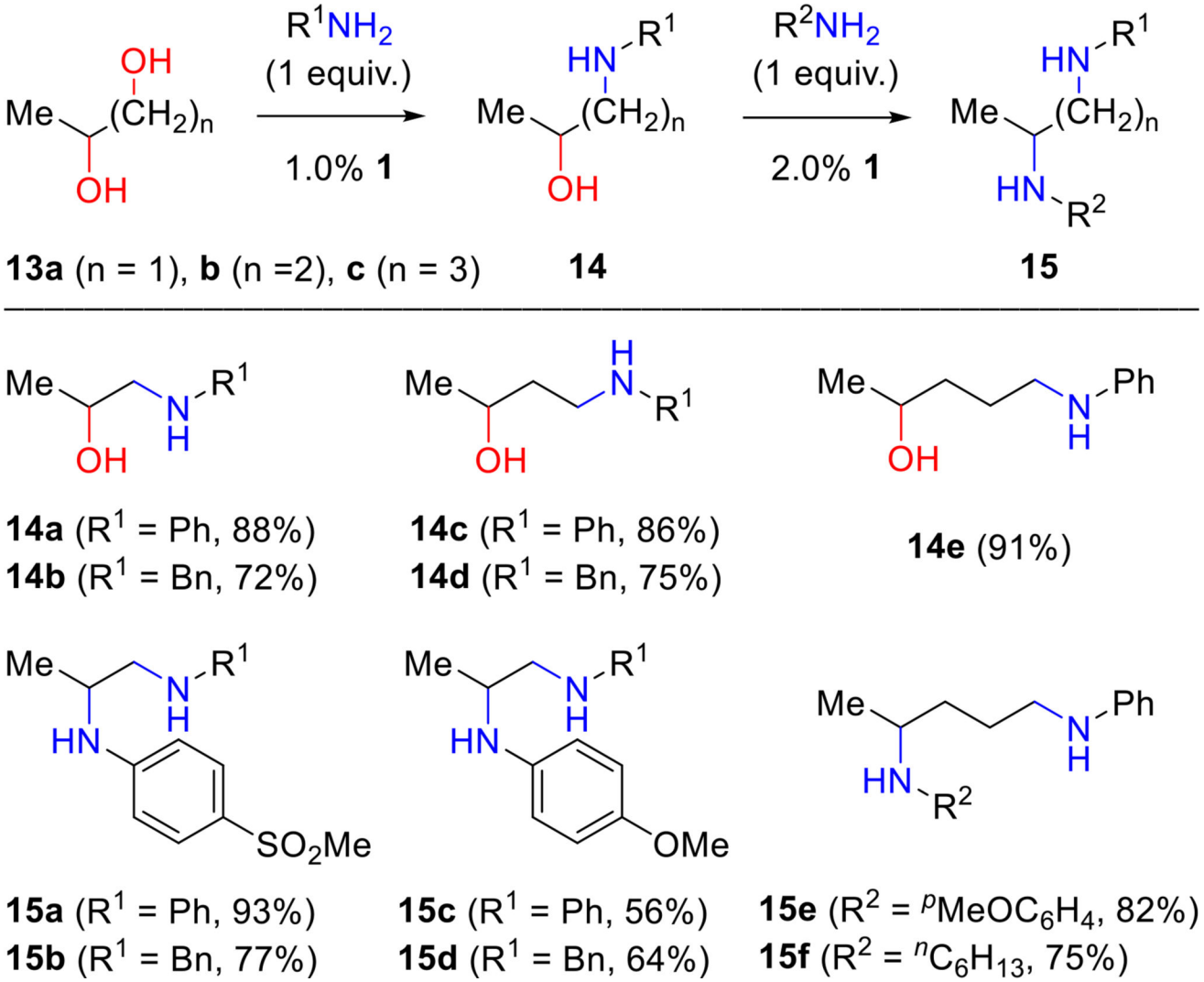


**Figure 6.**
Regioselective mono- and sequential diaminations of diols **13a–c**.

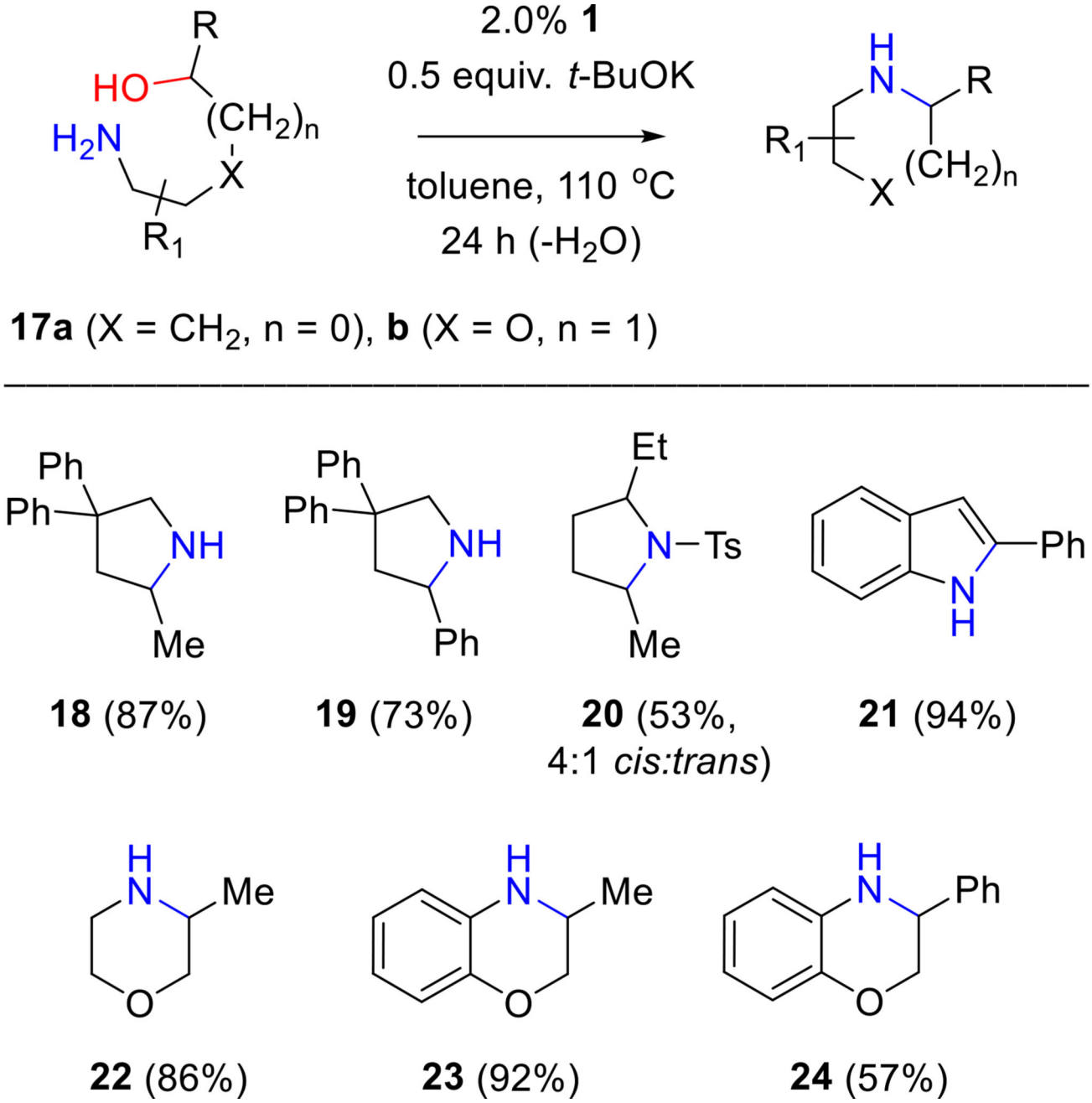


**Figure 7.**
Synthesis of five- and six-membered heterocycles via ruthenium-catalyzed BH cyclizations of aminoalcohols using complex **1**.

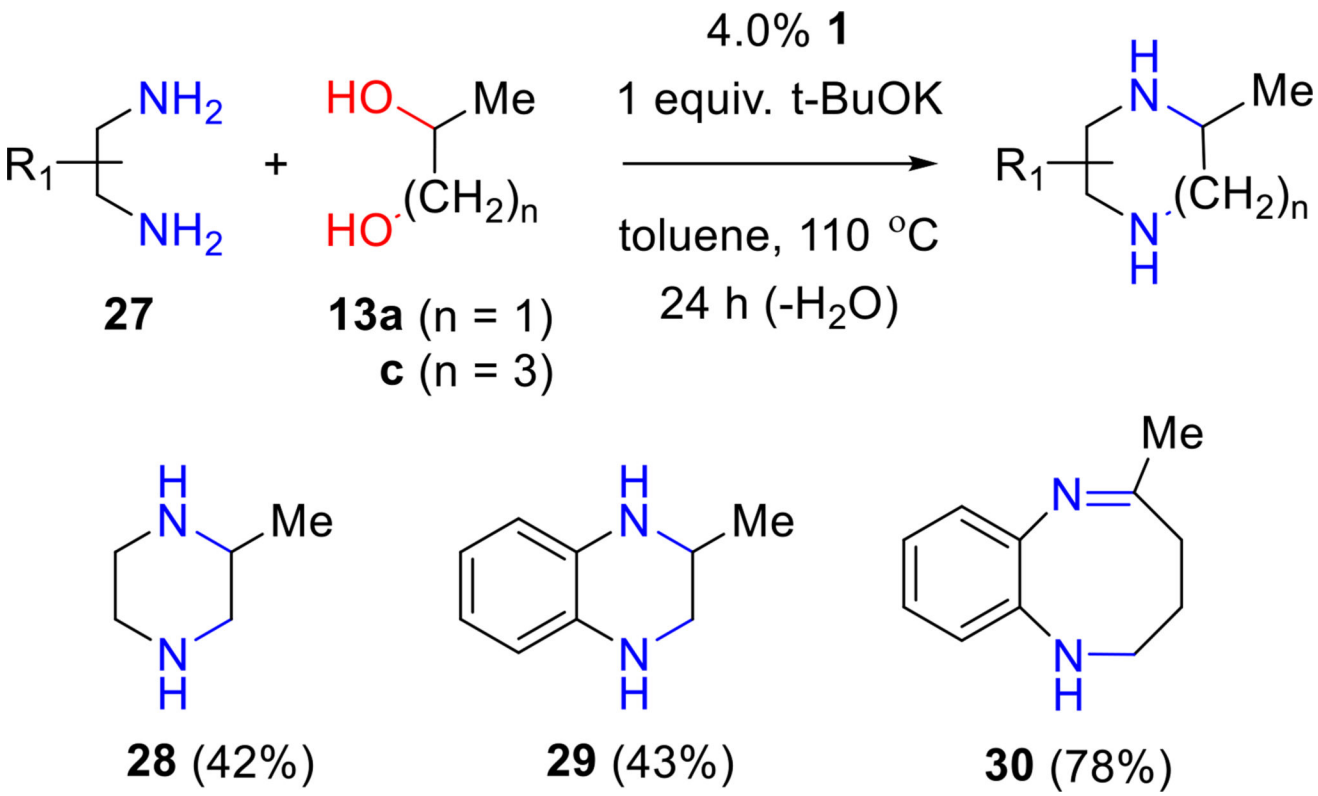


**Figure 8.**
Synthesis of piperazines and diazocines.