JOC Article

Samarium-Promoted Coupling of 1,10-Phenanthroline with Carbonyl Compounds for Synthesis of New Ligands†

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1,10-Phenanthroline reacts with aldehydes and ketones in the presence of samarium diiodide to produce 2-(1-hydroxyalkyl)-1,10-phenanthrolines. The hydroxyalkyl substituent can be functionalized in numerous ways or removed to permit further ligand variation. The carbonyl coupling reaction can also be repeated to provide 2,9-disubstituted phenanthrolines. Taken together, these operations provide ready access to a large number of phenanthroline derivatives to serve as ligand libraries for catalyst exploration.

Introduction

The development of new catalysts for enantioselective syntheses continues to grow in importance.[1] The pharmaceutical industry has demonstrated the crucial need for developing pure enantiomers of many drugs, and the most efficient method to obtain these compounds by stereoselective synthesis is through the use of chiral catalysts, whether natural (i.e., enzymes) or synthetic. To improve access to enantiomerically pure compounds, there is an ongoing need to develop new chiral catalysts. In turn, these chiral catalysts are most often obtained by complexation of metals with chiral ligands. Therefore, the development of suitable catalysts often becomes an exercise in exploring new ligands and their methods of preparation.

Included among the numerous types of ligands of demonstrated utility are bidentates containing two nitrogen donor atoms for coordination to metals. Especially widely investigated have been 2,2′-bipyridines and bis(1,3-oxazolin-2-yl)alkanes.[2,3] Also closely related in coordination chemistry are the 1,10-phenanthrolines, which serve as essentially universal ligands for metals of relevance in catalysis.[4] A special feature of phenanthrolines is their greater rigidity as a scaffold for ligand design compared to bipyridines and bis(oxazolines). Examples of applications of metal complexes of 1,10-phenanthrolines as catalysts include 1,3-dipolar cycloadditions;[5] aromatic and alkenyl aminations and amidations;[6] Heck reactions;[7] oxidation of alkenes,[8] arenes,[9] and alcohols;[10] alkene and alkyne cyclizations;[11] enolate allylations,[12] arylations,[13] alkylations, and Michael reactions;[14] conjugate additions to enones;[15] alkene cyclopropanation,[16] reductive carbonylation of nitroaromatics;[17] and CO/styrene copolymerization.[18] However, compared to bipyridines and bis(oxazolines), access to chiral forms

† This paper is dedicated to Professor Björn Åkermark on the occasion of his 70th birthday.

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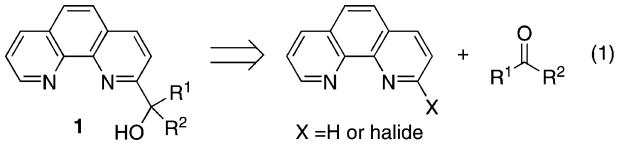
of phenanthrolines[19] and their applications in enantioselective synthesis have been more limited. Some examples include Rh-catalyzed asymmetric ketone hydrogenation[20] and hydrosilylation;[21] Zn-, Co-, Cu-, Ni-, and Cd-catalyzed enantioselective hydrolysis of amino acid esters;[22] Pd-catalyzed asymmetric allylation of enolates;[23] Cu-catalyzed allylic oxidations;[24] and Cu-catalyzed asymmetric alkene cyclopropanation.[25]

With the limited number of applications to date, there remains ample opportunity for additional development of chiral phenanthroline complexes. These further studies would be facilitated by the availability of several general methods for the synthesis of substituted phenanthroline derivatives. Substituted 1,10-phenanthrolines, including chiral derivatives, are most commonly synthesized by coupling of 2-halo- or 2,9-dihalo-1,10-phenanthrolines with various organometallic reagents, by lithiation of C(2) or C(9) followed by reaction with electrophiles, or by de novo construction such as the Friedländer synthesis of phenanthrolines.[19,26] However, to meet the goals of our work, we recognized a need for additional methods to complement these previously developed procedures.

Our overall aim was to use the parent 1,10-phenanthroline as a scaffold for chiral catalyst design. In the first of these studies, we had demonstrated the feasibility of employing a combined quantum mechanics/molecular mechanics approach for the design and computational screening of virtual libraries of catalysts.[27−29] This approach proved to be very successful in predicting the enantiomeric excesses of products of reactions using previously unknown chiral catalysts. Rather than needing to synthesize all of the members of a larger library of catalysts followed by experimental screening of their performance, we were able to limit the actual preparations to only very small, focused libraries of catalysts for which the best performances were predicted. A consequence of this approach was that we needed appropriate synthetic methods to access the ligands that resulted from the computational design efforts. Several of the chiral ligands for which the best performances were predicted could in general be derived from 2-(1-hydroxyalkyl)phenanthrolines (**1**). In turn, these compounds were envisioned as being the products of coupling of the parent 1,10-phenanthroline or 2-halo derivatives with chiral or prochiral aldehydes and ketones (eq 1). Several phenanthrolines potentially derivable from carbonyl-containing terpenes were especially promising candidates for catalyst exploration. Therefore, we initiated a study of methods to effect the desired coupling reactions.



(1)

Results and Discussion

Coupling Reactions. Our first efforts to obtain the targeted phenanthrolines **1** were based upon the generation of 2-metalated 1,10-phenthrolines and subsequent addition to carbonyl compounds. We explored the use of halogen−lithium exchange reactions of 2-halophenanthrolines with alkyllithium reagents and with active metals,[30] and we attempted direct lithiation of the parent phenanthroline with strong bases under several sets of conditions. In none of these attempts were useful results obtained upon addition of aldehydes or ketones to the reaction mixtures. In many cases, we obtained substantial quantities of simple 2-alkylphenanthrolines resulting from addition of alkyllithium reagents to the phenanthroline core, which is consistent with earlier methods of preparation of substituted phenanthrolines.[19]

As the basis for another approach, we saw a parallel between the desired overall reaction (eq 1) and pinacol-like coupling reactions of carbonyl compounds, either with themselves or, more importantly, with other unsaturated partners. In recent years, lanthanide-promoted reactions of this type have been very well studied, especially with samarium diiodide as the coupling reagent.[31] Single-electron-transfer (SET) pathways are involved in these reactions with several types of coupling substrates.[32] With respect to this previously reported work, the coupling that we aimed to effect was particu-

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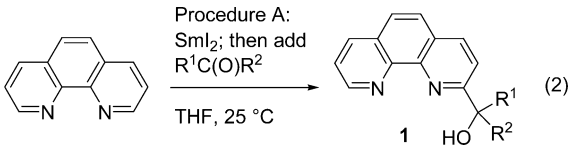
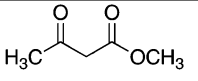
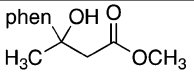
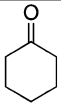
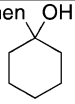
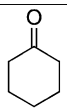
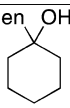
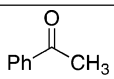
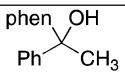
larly closely related to reactions of carbonyl compounds with indoles[33] and with thiophenes.[34] Other related reactions include the use of imines,[35] oxime ethers,[36] hydrazones,[37] nitrones,[38] nitriles,[36b,39] amides,[40] benzene derivatives,[41] and related substrates.[31,42]

Upon investigating the desired reaction, we observed in our initial studies that the treatment of 1,10-phenanthroline with SmI_2 followed by addition of alkyl ketones (procedure A) produces the targeted 2-substituted phenanthrolines **1** (eq 2) as coupling products in good yields (40−89%; the results are included later in Table 2 together with the results from using more recently developed conditions).[43] This reaction is very sensitive to moisture and air. Even very small amounts of water present in the reaction solutions can inhibit the reaction. 1,10-Phenanthroline is hygroscopic, and it is important that is has been thoroughly dried before use. Before realizing this very high sensitivity toward water, we had difficulty reproducing this reaction, but when adequate care is taken to maintain anhydrous conditions, the reaction reliably gives good results.



(2)

TABLE 1. Unsuccessful Attempts To Extend the Coupling Reaction with 1,10-Phenanthroline

substrate	coupling reagent	desired product (not obtained)
	SmI_2, THF[a]	
	SmI_2, $ZnCl_2$, THF	
	TmI_2, THF	
	TmI_2, THF	

[a] Procedure A was used in this experiment.

Under the originally developed conditions, this reaction was limited to the use of dialkyl ketones as substrates yielding tertiary alcohol products. When aryl ketones or alkyl and aryl aldehydes were used as substrates, the corresponding coupling products were not observed. Instead, pinacol self-coupling products were usually produced. Being able to perform the coupling of phenanthroline with substrates beyond simple dialkyl ketones would permit the generation of a more diverse collection of ligands. With this goal in mind, improvement of the reaction conditions for this coupling reaction was therefore investigated to permit the use of a broader range of carbonyl substrates.

Initial attempts to couple phenanthroline to a wider variety of carbonyl substrates under different conditions[44] failed. Table 1 summarizes these unsuccessful experiments.

After these unsuccessful attempts, we found that our previously observed coupling reaction with ketones could be performed more reliably under modified conditions whereby 1,10-phenanthroline and the ketone were premixed in solution and then SmI_2 was added at room temperature (procedure B). These conditions were then applied to the use of aldehydes, since earlier reactions (procedure A) had failed to produce the desired compounds. In a test reaction, addition of SmI_2 to a solution of 1,10-phenanthroline and propionaldehyde in THF produced the desired coupling product in 94% yield (eq 3).

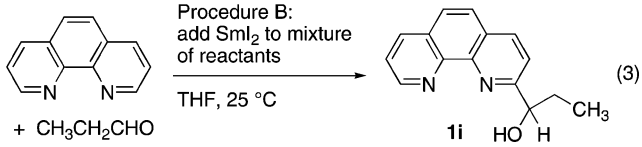


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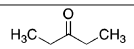
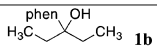
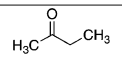
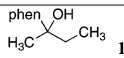
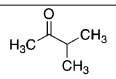
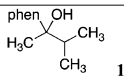
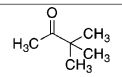
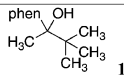
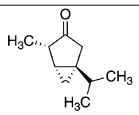
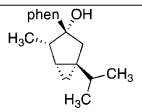
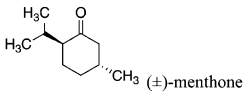
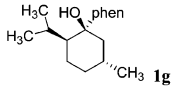
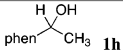
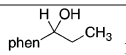
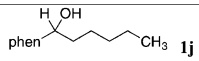
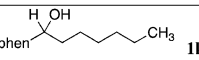
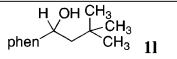
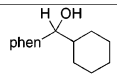
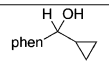
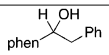
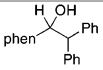
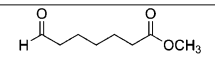
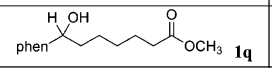
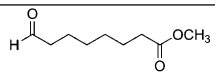
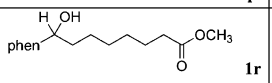
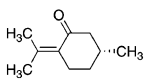
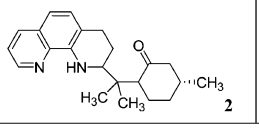
TABLE 2. Results of the Coupling of 1,10-phenanthroline with Ketones and Aldehydes

entry	substrate	coupling product	yield (%)
1[a]		 **1a**	88
2[a]		 **1b**	89
3[a]		 **1c**	73
4[a]		 **1d**	71
5[a]		 **1e**	40
6[a]	 (-)-thujone	 **1f**	45
7[a]	 (±)-menthone	 **1g**	54
8[b]	CH_3CHO	 **1h**	91
9[b]	CH_3CH_2CHO	 **1i**	94
10[b]	$CH_3(CH_2)_4CHO$	 **1j**	72
11[b]	$CH_3(CH_2)_5CHO$	 **1k**	85
12[b]	$(CH_3)_3CCH_2CHO$	 **1l**	87
13[b]		 **1m**	68
14[b]	Cyclopropane-carboxaldehyde	 **1n**	80
15[b]	$PhCH_2CHO$	 **1o**	72
16[b]	Ph_2CHCHO	 **1p**	64
17[b]		 **1q**	62
18[b]		 **1r**	94
19[a]	 (+)-pulegone	 **2**	50

[a] Procedure A was used in this experiment. [b] Procedure B was used in this experiment.

Table 2 summarizes the overall results for the SmI_2-promoted coupling of 1,10-phenanthroline with ketones and aldehydes under the two sets of conditions. The yields are usually good to excellent. The reaction has proven to be general for alkyl-substituted carbonyl compounds, but it continues to be unsuccessful for aromatic ketones and aldehydes, as was also the case in our initial studies.[43] Entries 17 and 18 show the expected compatibility with esters.[45] The lower yield in entry 17 may reflect possible formation of the corresponding lactone, which we did not attempt to isolate and characterize. α,β-Unsaturated carbonyl compounds do not generally give useful results as substrates in these coupling reactions. However, the reaction with pulegone (entry 19) gave a product **2** of undetermined stereochemistry, which results from conjugate addition and with the phenanthroline nucleus obtained in a reduced form. The addition to (−)-thujone produced a single diastereomer for which the stereochemistry was determined by NOESY studies on compound **3f** (Table 3). Also, the addition to *dl*-menthone produced a single diastereomer that resulted from equatorial attack on the carbonyl carbon as supported by ^{13}C NMR data.[46]

Further Reactions of the Coupling Products. In general, the new phenanthroline ligands that arise from our computational design of catalysts do not retain the hydroxy group that results from the above coupling reactions. Instead, the desired ligands either incorporate other substituents that can be derived from alcohols or the hydroxyl group is completely absent. Therefore, we needed to investigate methods for either modification or removal of this group.

One straightforward modification of the hydroxyalkylphenanthrolines **1** is *O*-alkylation to give ether derivatives. Employing sodium hydride and methyl iodide, we have obtained a series of 2-(1-methoxyalkyl)phenanthrolines **3** (eq 4). Similarly, *O*-acylation can be accomplished as exemplified by the use of acetic anhydride, pyridine, and DMAP with **1i** to give the acetate **4i** (eq 5). The results of these alkylations and acylations are summarized in Table 3. These reactions can in principle be extended to a range of other suitable alkylating and

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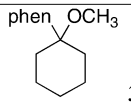
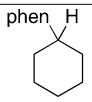
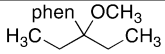
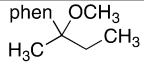
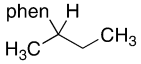
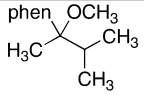
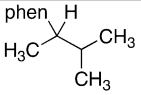
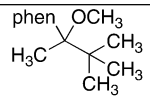
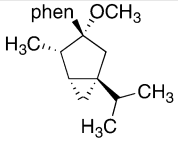
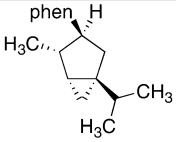
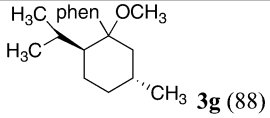
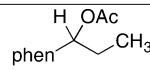
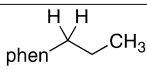
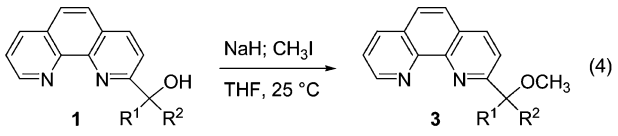
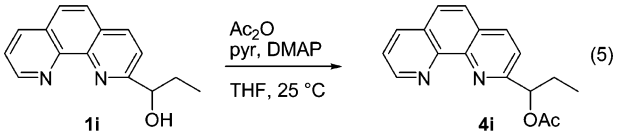
TABLE 3. Results of Further Reactions of the Ketone and Aldehyde Adducts

initial adduct	*O*-functionalization product (% yield)	Deoxygenation product (% yield)
1a	 **3a** (90)	 **5** (66)
1b	 **3b** (66)	--
1c	 **3c** (72)	 **5c** (45)
1d	 **3d** (70)	 **5d** (58)
1e	 **3e** (55)	--
1f	 **3f** (75)	 **5f** (68)
1g	 **3g** (88)	--
1i	 **4i** (94)	 **5i** (50)

acylating agents to increase again the diversity of available ligands.

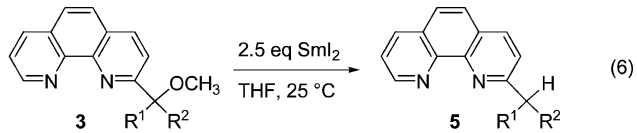


(4)

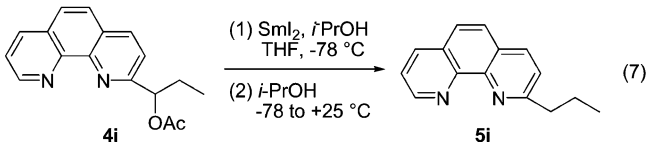


(5)

With respect to the potential need for removal of the oxygen substituent entirely from these ligands, either the ether or acetate derivatives are subject to reductive cleavage with SmI_2 to afford the 2-alkylphenanthrolines **5** (eqs 6 and 7). The acetate cleavage is made more complicated by competing deacetylation to regenerate the free hydroxy derivative **1i** as the major product.[47] However, when performed in the presence of 2-propanol at low temperature, the amount of **1i** produced was significantly decreased. Nonetheless, the demethoxylation reaction is more useful than the deacetoxylation at this point in the development of these cleavages. The overall results of these deoxygenations are compiled in Table 3 along with the previous functionalizations.



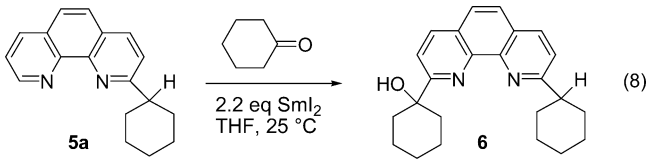
(6)



(7)

These general types of reductive cleavage reactions are well-known for SmI_2 and related reagents. Very well developed are cleavages adjacent to carbonyl groups and similarly functionalized systems.[31] Especially relevant to our observations are the previously reported SmI_2-promoted deoxygenation reactions of (1-hydroxyalkyl)-pyridines and the corresponding acetates.[48]

One final observation is that a deoxygenation product may be resubjected to the initial carbonyl coupling reaction to provide a 2,9-disubstituted phenanthroline **6** (eq 8).



(8)

Conclusions

The SmI_2-promoted reactions of 1,10-phenanthroline with ketones and aldehydes provides a broad array of new substituted phenanthrolines. These coupling reactions together with further reactions of the products, including *O*-alkylation, *O*-acylation, and deoxgenation, as well as additional coupling at C(2) after initial coupling at C(9), provide a tremendous level of diversity for exploration of new catalysts. The diversity elements that may be investigated in applications of these ligands are summarized in Figure 1. Many uses in catalysis may be anticipated in further studies, and applications in the synthesis of alkaloids and other nitrogen-containing compounds are also likely. In our own ongoing investigations, we are now well positioned to prepare the many ligands that will be generated by means of our virtual catalyst design and screening efforts.

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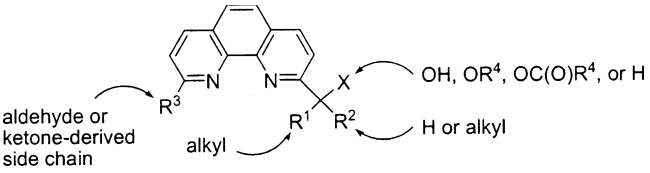

FIGURE 1. Diversity elements generated in the 1,10-phenanthroline functionalization reactions reported in this paper.

Experimental Section

Representative Procedure A (1a−g). 2-(1-Hydroxycyclohexyl)-1,10-phenanthroline (1a). To a stirred solution of 1,10-phenanthroline (0.1 g, 0.55 mmol) in THF (5 mL) was added a 0.1 M solution of SmI_2 in THF (12.2 mL, 1.22 mmol) at 25 °C. After being stirred for 5 min, 0.120 g (1.22 mmol) of cyclohexanone was added, and the resulting mixture was stirred for 12 h at 25 °C and monitored by TLC. Upon completion of the reaction, satd aq NH_4Cl was added to quench the reaction, and the resulting mixture was extracted with CH_2Cl_2. The organic extracts were combined, washed with brine, dried over $MgSO_4$, filtered, and concentrated. Column chromatography (alumina, ethyl acetate/hexane gradient) provided 0.134 mg (88%) of **1a** as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.18 (dd, J = 4.20, 1.8 Hz, 1H), 8.28 (d, J = 8.4 Hz, 1H), 8.27 (dd, J = 8.4, 1.8 Hz, 1H), 7.82 (d, J = 8.8 Hz, 1H), 7.79 (d, J = 8.8 Hz, 1H), 7.76 (d, J = 8.4 Hz, 1H), 7.65 (dd, J = 8.1, 4.5 Hz, 1H), 2.08−1.71 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.5, 150.3, 145.8, 144.0, 137.2, 136.1, 129.0, 127.5, 126.3, 126.2, 122.9, 119.2, 73.5, 38.6, 23.7, 22.2; IR ($CHCl_3$) 3352, 3048, 2928, 909 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{18}H_{19}N_2O$ (M + H$^+$) 279.1497, found 279.1490.

Representative Procedure B (1h−r). 2-(1-Hydroxyheptyl)-1,10-phenanthroline (1k). In a flame-dried 25 mL round-bottom, one neck flask under argon, 36 mg (0.2 mmol) of 1,10-phenanthroline was dissolved in 2 mL of degassed anhydrous THF. To this was added 0.056 mL (0.4 mmol) of heptaldehyde, and after the mixture was stirred briefly, 5 mL of 0.1 mL of 0.1 M SmI_2 in THF was added and the mixture was allowed to stir at room temperature for 1 h. The reaction was quenched with 1 N HCl (aq), and the mixture was partitioned between satd $NaHCO_3$ (aq) and CH_2Cl_2. The layers were separated, and the aqueous layer was extracted with CH_2Cl_2 (2 × 20 mL). The organic solution was dried over $MgSO_4$ and concentrated under vacuum. The residual orange oil was purified by column chromatography (50:1 CH_2Cl_2 (saturated with NH_3)/MeOH, silica gel) yielding 50 mg (85%) of 2-(1-hydroxyheptyl)-1,10-phenanthroline (**1k**) as an orange oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.13 (dd, J = 4.3, 1.7 Hz, 1H), 8.20 (dd, J = 7.7, 1.7 Hz, 1H), 8.18 (d, J = 8.1 Hz, 1H), 7.72 (m, 2H), 7.56 (dd, J = 8.0, 4.3 Hz, 1H), 5.20 (dd, J = 7.9, 4.7 Hz, 1H), 1.94 (m, 2H), 1.56 (m, 2H), 1.26 (m, 6H), 0.83 (t, J = 6.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) d 164.5, 150.3, 145.9, 144.9, 136.8, 136.4, 129.1, 127.9, 126.7, 126.1, 123.0, 120.7, 77.7, 77.2, 76.8, 74.8, 39.0, 32.0, 29.6, 25.9, 22.8, 14.2; IR (film) 3350, 1619, 1591, 852 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{19}H_{23}N_2O$ (M + H$^+$) 295.1810, found 295.1790.

2-[1-Methyl-1-[(4*R*)-4-methyl-2-oxocyclohexyl]ethyl]-1,2,3,4-tetrahydrophenanthroline (2). Through use of the above general procedure A, (*R*)-(+)-pulegone (0.186 g, 1.22 mmol) was converted into 0.092 g (50%) of **2** as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.66 (dd, J = 3.9, 1.5 Hz, 1H), 7.97 (dd, J = 8.4, 1.8 Hz, 1H), 7.28 (dd, J = 8.4, 4.5 Hz, 1H), 7.02 (d, J = 8.1 Hz, 1H), 6.92 (d, J = 8.10 Hz, 1H), 5.93 (br s, 1H), 4.57 (br s, 1H), 2.71 (dt, J = 11.6, 4.3 Hz, 1H), 2.46 (m, 2H), 2.25 (m, 1H), 2.10 (m, 2H), 1.93 (m, 3H), 1.24 (m, 3H), 1.1 (s, 3H), 1.09 (s, 3H), 0.92 (d, J = 6.9 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.4, 147.2, 138.4, 136.6, 135.9, 128.9, 128.0, 122.9, 120.6, 112.9, 65.1, 60.3, 55.2, 59.1, 59.0, 29.4, 29.3, 29.0, 28.6, 27.5, 23.9, 19.8; IR ($CHCl_3$) 3436, 2956, 1688, 909 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{22}H_{29}N_2O$ (M + H$^+$) 335.2123, found 335.2134.

Representative Procedure for Synthesis of 2-(Methoxyalkyl)phenanthrolines (3a−g). 2-(1-Methoxycyclohexyl)-1,10-phenanthroline (3a). To a stirred solution of 0.320 g (1.15 mmol) of **1a** in THF was added 0.110 g (4.6 mmol) of NaH in one portion followed by 0.65 mL (4.6 mmol) of MeI. The mixture was stirred at 25 °C and monitored by TLC. Upon completion of the reaction, satd aq NH_4Cl was added to quench the reaction, and the resulting mixture was extracted with CH_2Cl_2. The organic extracts were combined, washed with brine, dried over $MgSO_4$, filtered, and concentrated. Purification by column chromatography (alumina gel, ethyl acetate/hexane gradient) yielded 0.301 g (90%) of **3a** as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.24 (dd, J = 4.5, 1.8 Hz, 1H), 8.25 (d, J = 8.4 Hz, 1H), 8.25 (dd, J = 8.1, 2.4 Hz, 1H), 7.96 (d, J = 8.4 Hz, 1H), 7.82 (d, J = 8.8 Hz, 1H), 7.75 (d, J = 8.80 Hz, 1H), 7.61 (dd, J = 8.1, 4.5 Hz, 1H), 3.11 (s, 3H), 2.23 (m, 4H), 1.74 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 166.3, 150.5, 146.3, 145.1, 136.4, 136.0, 128.8, 127.4, 126.4, 126.0, 122.4, 120.5, 80.5, 50.6, 33.8, 25.1, 21.7; IR ($CHCl_3$) 3048, 2933, 908 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{19}H_{21}N_2O$ (M + H$^+$) 293.1654, found 293.1665.

2-(1-Acetoxypropyl)-1,10-phenanthroline (4i). In a 50 mL flame-dried round-bottom flask under argon was dissolved 95 mg (0.4 mmol) of 2-(1-hydroxypropyl)-1,10-phenanthroline (**1i**) in 3 mL of anhydrous THF, and to it were added 0.08 mL (0.8 mmol) of acetic anhydride, 0.08 mL (1.0 mmol) of pyridine, and a catalytic amount of DMAP. The reaction was stirred at room temperature for 17 h, concentrated under reduced pressure, and purified by column chromatography (50:1, CH_2Cl_2 (saturated with NH_3)/MeOH, silica gel) yielding 103 mg (92%) of 2-(acetoxypropyl)-1,10-phenanthroline as an orange oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.24 (dd, J = 4.5, 2 Hz, 1H), 8.24 (d, J = 7.9 Hz, 1H), 8.23 (dd, J = 8.2, 1.5 Hz, 1H), 7.78 (d, J = 8.9 Hz, 1H), 7.76 (d, J = 8.9 Hz, 1H), 7.69 (d, J = 8.4 Hz, 1H), 7.62 (dd, J = 8.2, 4.0 Hz, 1H), 6.26 (dd, J = 8.2, 4.5 Hz, 1H), 2.22 (m, 1H), 2.20 (s, 3H), 2.11 (m, 1H), 1.01 (t, J = 7.4 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.6, 161.0, 150.6, 146.3, 145.8, 137.0, 136.3, 129.2, 128.1, 126.6, 126.5, 123.1, 120.0, 19.0, 77.5, 77.2, 77.0, 29.1, 21.4, 10.0; IR (film) 2971, 2935, 1737, 1620, 1589, 1236, 853 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{17}H_{17}N_2O_2$ (M + H$^+$) 281.1290, found 281.1297.

Representative Procedure for SmI_2-Mediated Demethoxylation of 2-(Methoxyalkyl)phenanthrolines (5a,c,d,f). 2-(Cyclohexyl)-1,10-phenanthroline (5a). To a stirred solution of 0.200 g (0.684 mmol) of **3a** in THF (5 mL) was added 17.1 mL (1.71 mmol) of a 0.1 M solution of SmI_2 in THF at 25 °C. The mixture was stirred at 25 °C and monitored by TLC. Upon completion of the reaction, satd aq NH_4Cl was added to quench the reaction, and the resulting mixture was extracted with CH_2Cl_2. The organic extracts were combined, washed with brine, dried over $MgSO_4$, filtered, and concentrated. Purification by column chromatography (alumina, ethyl acetate/hexane gradient) yielded 0.119 g (66%) of **5a** as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 9.19 (dd, J = 4.5, 1.8 Hz, 1H), 8.16-(dd, J = 8.1, 1.8 Hz, 1H), 8.12 (d, J = 8.4 Hz, 1H), 7.71 (d, J = 8.8 Hz, 1H), 7.64 (d, J = 8.8 Hz, 1H), 7.54 (dd, J = 8.1, 4.2 Hz, 1H), 7.53 (d, J = 8.4 Hz, 1H), 3.33 (tt, J = 3.00−3.30 Hz, 1H), 2.12−1.28 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.5, 150.2, 146.1, 145.3, 136.3, 135.9, 128.7, 127.1, 126.3, 125.4, 122.5, 120.5, 47.7, 33.3, 26.3, 26.0; IR ($CHCl_3$) 3049, 2929, 908 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{18}H_{19}N_2$ (M + H$^+$) 263.1548, found 263.1534.

2-Propyl-1,10-phenanthroline (5i). In a 25 mL flame-dried round-bottom flask under argon was dissolved 41 mg (0.15 mmol) of 2-(1-acetoxypropyl)-1,10-phenanthroline (**4i**) in 2 mL of anhydrous THF and the mixture cooled to −78 °C. To this solution was added 0.01 mL of 2-propanol followed by 4 mL (0.4 mmol) of 0.1 M SmI_2 in THF, and after being stirred for 20 min at this temperature the reaction was quenched with an excess of 2-propanol. The reaction mixture was partitioned between satd $NaHCO_3$(aq) and CH_2Cl_2. The layers were separated, and the aqueous layer was extracted with CH_2Cl_2

(2 × 20 mL). The organic layers were combined, dried over $MgSO_4$, and concentrated under reduced pressure. Column chromatography (50:1, CH_2Cl_2 (saturated with NH_3)/MeOH, silica gel) yielded 17 mg (50%) of 2-propyl-1,10-phenanthroline (**5i**) as an orange oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.23 (dd, J = 4.5, 1.5 Hz, 1H), 8.23 (dd, J = 7.9, 2.0 Hz, 1H), 8.16 (d, J = 8.4 Hz, 1H), 7.77 (d, J = 8.9 Hz, 1H), 7.73 (d, J = 8.9 Hz, 1H), 7.61 (dd, J = 8.2, 4.5 Hz, 1H), 7.54 (d, J = 8.4 Hz, 1H), 3.2 (m, 2H), 1.92 (m, 2H), 1.07 (t, J = 7.4 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 163.7, 150.5, 146.4, 146.0, 136.4, 136.2, 129.9, 127.1, 126.7, 125.7, 123.0, 122.9, 77.5, 77.2, 77.0, 41.7, 24.0, 14.4; IR (film) 2960, 2870, 1620, 1590, 1553, 850 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{15}H_{15}N_2$ (M + H$^+$) 233.1235, found 233.1223.

9-(1-Cyclohexyl)-2-(1-hydroxycyclohexyl)-1,10-phenanthroline (6). Through use of the above general procedure A for addition of ketones to phenanthrolines, cyclohexanone (0.094 g, 0.953 mmol) was added to **5a** (0.100 g, 0.381 mmol) and 0.1 M SmI_2 (8.38 mL, 0.838 mmol) and converted into 0.083 g (60%) of **6** as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.24 (d, J = 8.4 Hz, 1H), 8.14 (d, J = 8.4 Hz, 1H), 7.76 (d, J = 8.8 Hz, 1H), 7.70 (d, J = 8.8 Hz, 1H), 7.66 (d, J = 8.4 Hz, 1H), 7.52 (d, J = 8.4 Hz, 1H), 3.06 (tt, J = 11.85, 3.30 Hz, 1H), 2.18−1.74 (m, 10H), 1.52−1.33 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 167.0, 165.3, 144.9, 143.4, 137.2, 136.0, 127.5, 127.3, 126.2, 124.9, 121.5, 118.7, 73.2, 47.2, 36.8, 32.8, 26.6, 26.1, 25.8, 22.7; IR ($CHCl_3$) 3338, 3042, 2927, 852 cm^{-1}; HRMS (FAB$^+$, m/z) calcd for $C_{24}H_{29}N_2O$ (M + H$^+$) 361.2280, found 361.2272.

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Supporting Information Available: Details for the preparation of compounds **1b**−**j**,**l**−**r**, **3b**−**g**, and **5c**,**d**,**f** as well as ^{1}H and ^{13}C NMR data for compounds **1a**−**r**, **2**, **3a**−**g**, **4i**, **5a**,**c**,**d**,**f**,**i**, and **6**. This material is available free of charge via the Internet at http://pubs.acs.org.

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