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Aminomethyl-Substituted Ferrocenes and Derivatives: Straightforward Synthetic Routes, Structural Characterization, and Electrochemical Analysis

Nejib Dwadnia,[†,⊥] Fatima Allouch,[†,⊥] Nadine Pirio,[†] Julien Roger,[†] Hélène Cattey,[†] Sophie Fournier,[†] Marie-Josée Penouilh,[†] Charles H. Devillers,[†] Dominique Lucas,[†] Daoud Naoufal,[‡] Ridha Ben Salem,[§] and Jean-Cyrille Hierso*[,†,∥]

[†]Université de Bourgogne, Institut de Chimie Moléculaire de l'Université de Bourgogne, UMR-CNRS 6302, 9 avenue Alain Savary, 21078 Dijon, France

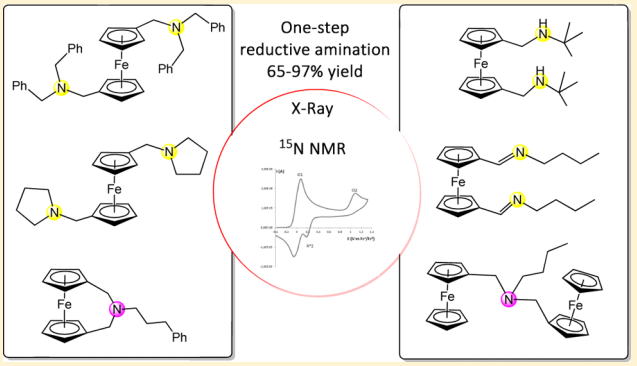
[‡]Université Libanaise, Faculté des Sciences, Laboratoire de Chimie de Coordination Inorganique et Organométallique, Beyrouth-Hadath, Lebanon

[§]Université de Sfax, Faculté des Sciences, Laboratoire de Chimie Organique Physique, UR11ES74 3038 Sfax, Tunisia

[∥]Institut Universitaire de France (IUF), France

Supporting Information

ABSTRACT: A variety of aminomethyl-substituted ferrocenes and the parent compounds (iminomethyl)ferrocenes, azaferrocenophanes, and diferrocenylamines can be selectively synthesized from reductive amination of 1,1′-diformylferrocene or formylferrocene. The optimized one- or two-step reactions have delivered 13 new compounds, isolated in 65−97% yields, which include tertiary (ferrocenylmethyl)amines and azaferrocenophanes by using $NaBH(OAc)_3$ as a mild reducing agent and (iminomethyl)ferrocenes and secondary (ferrocenylmethyl)amines by using $LiAlH_4$. X-ray structures of representative members of these ferrocene derivative families have evidenced the preferred conformation adopted by ferrocene backbones, in which surprisingly the steric hindrance is apparently not systematically minimized. ^{15}N NMR measurements on aminomethyl-substituted ferrocenes and derivatives are provided for the first time, establishing benchmark values ranging from 70 to 95 ppm (nitromethane δ 0 ppm). The cyclic voltammetry of these species evidences two clearly distinct oxidation potentials related to the iron(II) center and the amino function. These aminomethyl-substituted ferrocenes are potentially valuable for further *ortho*-directed functionalization of ferrocene.



INTRODUCTION

Functionalized ferrocene derivatives are molecular edifices for which a wide range of useful applications exist, particularly in close relationship with homogeneous catalysis, electrochemistry, material and polymer sciences, and biomedical research.[1] Driven by transition-metal-catalyzed applications, either enantioselective[1d,2] or achiral,[3] the synthesis of ferrocene derivatives incorporating atoms with donor bonding abilities such as phosphorus atoms has attracted much attention. Nitrogen-substituted ferrocenes have been comparatively much less developed, even though a significant amount of works and molecules have been reported since the 1950s.[4] The synthesis of 1,1′-diaminoferrocene[5] (Scheme 1, **A**) has allowed the development of 1,1′-ferrocene diamines (**B**)[6] and iminoferrocenes (**C**),[6c,7] successfully applied in catalytic olefin polymerization and oligomerization reactions promoted by either early (Ti, Zr) or late transition metals (Ni).[7,8,4] Notably, amido complexes are accessible from **B** by deprotonation of the secondary amine.

Before the work of McGowan and co-workers,[9] only sporadic examples of the related (aminoalkyl)ferrocene derivatives (Scheme 1, **E** and **D**), which incorporate an alkyl spacer between the ferrocene platform and a nitrogen-containing moiety (mainly amines), had been reported. Concerning aminomethyl-substituted ferrocenes (structures **E** and **D** in which $n = 1$), which are invaluable building blocks,[10] the need for more efficiency and diversification in the synthetic modes is clearly required: in particular with fewer synthetic steps, better yields, and not being limited to the introduction of aliphatic alkyl amines $-NMe_2$ and $-NEt_2$.[11−13] McGowan and co-workers reported the syntheses of 14 compounds of type **E** (n

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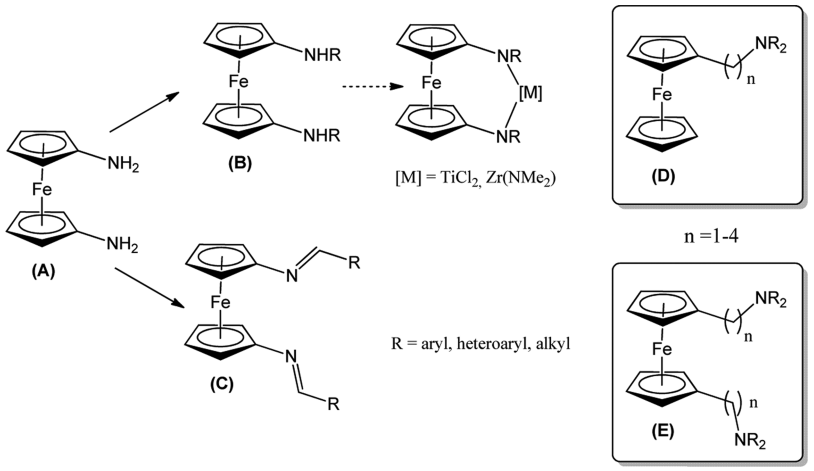
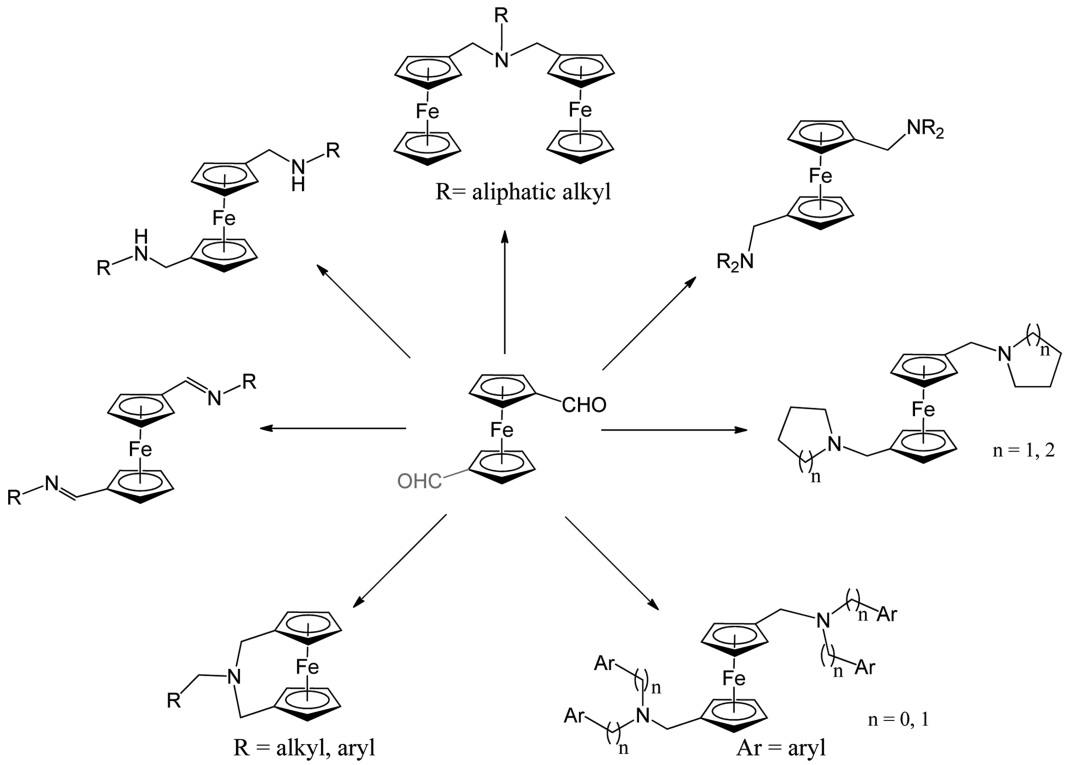
Scheme 1. Nitrogen-Substituted Ferrocenes: (Aminoalkyl)ferrocene Derivatives D and E



Scheme 2. Targeted Aminomethyl-Substituted Ferrocenes and Parent Compounds



= 2−4) by addition of 2 equiv of adequately substituted cyclopentadienyl salts to $FeCl_2$, and a single example of an aminomethyl-substituted ferrocene with a methylene spacer (n = 1) bearing a 2-pyridinyl group has been described (yield 48%).[9]

Reductive amination of carbonyl compounds is a powerful reaction in organic chemistry, able to deliver in high yield primary, secondary, and tertiary amines with a great variety of substituents.[14] Mild and selective synthetic conditions can be optimized if a convenient reducing agent is identified. We thus explored in more detail the synthesis of easily available ferrocene mono- and dicarbaldehydes for the production of aminomethyl-substituted ferrocene derivatives, as depicted in Scheme 2. We report herein the straightforward syntheses of a variety of aminomethyl-substituted ferrocenes and parent compounds ((iminomethyl)ferrocenes, azaferrocenophanes, diferrocenylamines) in excellent yields. A cautious characterization by X-ray diffraction in the solid state of these species has been performed, which highlights different preferred conformations for their ferrocene backbones. Multinuclear NMR in solution includes rarely reported ^{15}N NMR measurements. The characterization of the (aminomethyl)ferrocenes and parent compounds has been extended to electrochemical analysis, for which voltammetric behavior is shown to be influenced by both the iron center and the nitrogen-containing part of the molecules.

RESULTS AND DISCUSSION

Reactivity of Secondary Amines. Reductive amination of ferrocenecarbaldehyde has been previously reported as a few single examples with various reductive agents. 1,6-Diferrocenyl-2,5-diazahexane has been prepared from the monocarbaldehyde

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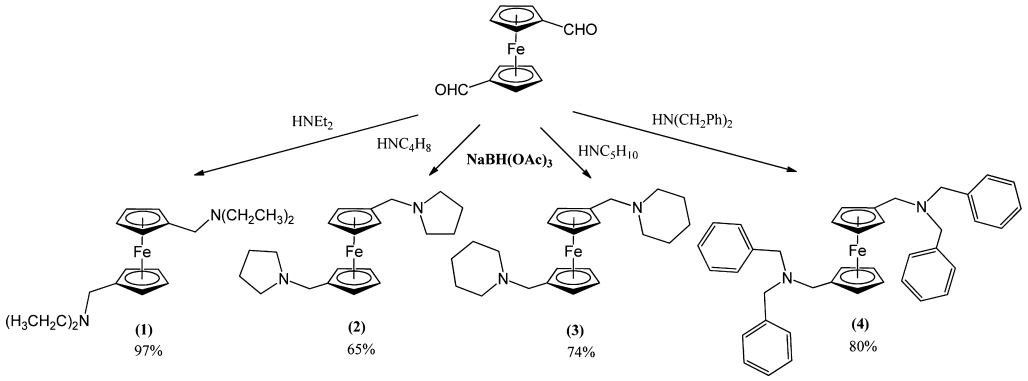
Scheme 3. (Aminomethyl)ferrocenes from Aliphatic and Cyclic Secondary Amines



formylferrocene reacted with 1,2-diaminoethane followed by reduction with $LiAlH_4$.[15] Formylferrocene has been also employed in reductive amination using the milder $NaBH(OAc)_3$ to produce *N,N*-(dimethyl)aminomethylferrocene[16] as well as bis(ferrocenylmethyl)cyclen.[17] $NaBH_4$ has been employed with the dicarbaldehyde ferrocene-1,1′-dicarboxaldehyde to form in moderate yield *N,N′*-(diisopropyl)-1,1′-ferrocenylmethyldiamine.[12e] We identified $NaBH(OAc)_3$ as best suited to achieve the reduction of the ferrocene iminium formed from reaction of 1,1′-diformylferrocene with the secondary amine Et_2NH in dichloroethane, which gives 1,1′-bis((*N,N*-diethylamino)methyl)ferrocene **1** (Scheme 3).

Under the optimized reaction conditions, **1** was formed in high yield (97%)[18] as a deep red oily product. It was characterized in ^1H NMR (solution in $CDCl_3$) by the following signals: for ethyl group protons signals at 1.02 (t) and 2.43 ppm (q), for protons of the methylene spacer a signal at 3.48 ppm (s), and for cyclopentadienyl ring (Cp) protons signals at 4.05 and 4.08 ppm. In ^{13}C NMR, signals for Cp are found at 83.4, 71.7, and 68.7 ppm, methylene carbons at 52.2 and 46.5 ppm, and the carbon methyl groups at 12.1 ppm. Due to the oily nature of **1**, no solid-state X-ray diffraction analysis could be performed. We thus achieved further characterization of the compound by examining its ^{15}N NMR; these data are in general fairly scarce in the literature. Due to the low natural abundance of the heavier isotope ^{15}N (0.36%), two-dimensional Fourier transform NMR techniques are more appropriate to determine the related chemical shift.[19] Heteronuclear multiple bond correlation (HMBC) sequences allowed us to correlate $^2J_{HN}$ and $^3J_{HN}$ (for $N(CH_2)$ and $N(CH_2CH_3)$ groups, respectively) ranging between 5 and 8 Hz with the corresponding ^{15}N chemical shift found at 76.0 ppm in $CDCl_3$.[20] To the best of our knowledge, such data have never been reported for (aminoalkyl)ferrocenes, and thus, values provided here now constitute a benchmark.[21]

The reductive amination conditions were applied without notable changes to the more hindered cyclic secondary amines pyrrolidine and piperidine, as well as dibenzylamine, to give in satisfactory to good yields the (aminomethyl)ferrocenes **2** (65%), **3** (74%), and **4** (80%), respectively (Scheme 3). A summary and comparison of their pertinent NMR data is provided in Table 1.

Hydrogen, carbon, and nitrogen resonances for the aliphatic alkyl amines **1** and **4** are very similar, while differences are found with cyclic amines concerning the more sensitive carbon and nitrogen nuclei. Concerning the latter, the five-membered pyrrolidinyl cycle of **2** exhibits a ^{15}N chemical shift at 86.0 ppm

Table 1

(aminomethyl) ferrocene	$\delta(^1H)$ Cp−CH_2 (ppm)	$\delta(^{13}C)$ Cp−CH_2 (ppm)	$\delta(^{15}N)$ (ppm)[a]	$\delta(^1H)$ Cp (ppm)	$\delta(^{13}C)$ Cp (ppm)
1	3.48	52.2	76.0	4.05, 4.08	68.7, 71.7, 83.4
2	3.43	55.1	86.0	4.05, 4.12	68.6, 70.4, 83.9
3	3.33	58.8	79.0	4.04, 4.08	68.5, 71.0, 82.7
4	3.47	52.2	74.8	3.96, 3.99	68.4, 70.6, 83.2

[a] CH_3NO_2 at 0.0 ppm was used as reference.

which is significantly deshielded in comparison to its congeners, possibly due to steric reasons.[22] In order to further explore the structural features of these species, we conducted solid-state X-ray diffraction studies. Figures 1−3 depict the molecular structures obtained for (aminomethyl)ferrocenes **2**−**4**, respectively. Compound **2** crystallizes in the centrosymetric *Pbcn* group. The iron atom is located on a C_2 axis. The Cp rings are in an almost eclipsed conformation, and the torsion angle C6−Ct−Ct^i−C6^i is equal to 64.27(7)°. The molecule belongs to the C_2 point group. Compound **3** crystallizes in the centrosymetric $P2_1/c$ group. The molecule is located on an inversion center consistent with a staggered conformation of the Cp rings in which the cyclic amine are in mutually *trans* positions (C6−Ct−Cti−C6 = 180°). The molecule belongs to the C_i point group.

Compound **4** crystallizes in the space group $P\bar{1}$, and two rotamers **A** and **B** coexist in the unit cell in the ratio 2:1. The rotamer **A** (Figure 3, top) belongs to the C_2 point group (noncrystallographic axis), and its amino groups have a *cisoid* conformation with a torsion angle C11−Ct1−Ct2−C26 of 49.22(9)°, reminiscent of the conformation found for compound **2**. In relation to the existence of a crystallographic inversion center, the rotamer **B** conversely exhibits a *transoid* conformation, similar to what was observed for **3** (Figure 3, bottom).

The coexistence of rotamers in crystals has been also reported for 1,1′-diformylferrocene,[23] albeit with conformers and mutual ratios different from those observed for **4**. In the case of 1,1′-diformylferrocene one eclipsed and one staggered conformation of cyclopentadienyl rings is observed for the rotamers (with dihedral angles for C−C bonds holding formyl groups of about 137.8 and 42.9°, respectively). For **4**, cyclopentadienyl ring conformations are staggered in both rotamers, leading to wider dihedral angles C11−Ct1−Ct2−C26

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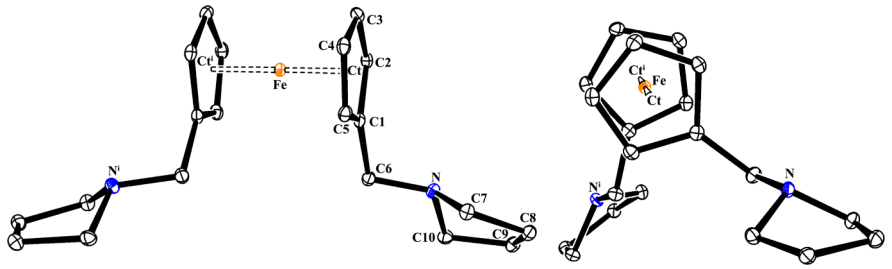

Figure 1. Molecular structure of **2** (left) and view from above (right). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Fe−Ct = 1.6498(18), N−C6 = 1.462(2), N−C7 1.465(2), N−C10 = 1.459(2); Ct−Fe−Ct^{i} = 179.65(8), C6−N−C7 = 114.61(13), C6−N−C10 = 114.81(13), C7−N−C10 = 103.61(13); C6−Ct−Ct^{i}−C6^{i} = 64.27(7). Symmetry transformation: (i) 2 − *x*, *y*, −*z* + 1.5.

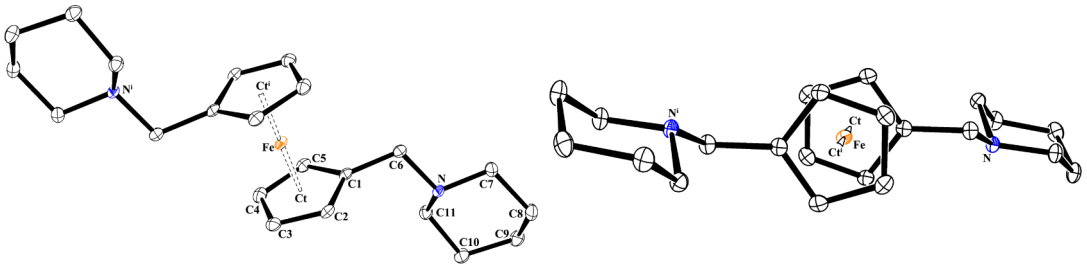

Figure 2. Molecular structure of **3** (left) and view from above (right). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Fe−Ct = 1.6549(19), N−C6 = 1.468(2), N−C7 = 1.459(3), N−C11 = 1.462(3); C6−N−C7 = 111.10(15), C6−N−C11 = 112.21(15), C7−N−C11 = 110.28(15). Symmetry transformation: (i) −*x*, −*y*, −*z*.

and C46−Ct3−Ct3′−C46′ of about 49.2 and 180.0°, respectively. Concerning 1,1′-diformylferrocene, the coexistence of these rotamers has been attributed to the presence of CO acceptor groups and of several C−H donors that may play a role in controlling the crystal packing.[23] This explanation is probably not valid in the case of **4**, for which N···H−C interactions are absent in the rotamers. In any case, apparently the steric hindrance in the ferrocenyl conformation is not systematically minimized. We found some synthetic limitations of the reductive amination method with diisopropylamine, HN(*i*-Pr)$_2$, and with the secondary diarylamine we tested, HNPh$_2$, despite the use of other stronger reductive agents such as NaBH$_4$.

Reactivity of Primary Amines. To further explore the access to various (aminomethyl)ferrocene structures, we tested the reactivity of primary amines to generate secondary amine species susceptible to give amido coordination complexes upon deprotonation in the presence of metals (similarly to the evolution of **B** in Scheme 1). Various primary amines were tested, and following the general conditions established for the synthesis from secondary amines, we observed in each case notable troubles of selectivity (Scheme 4). For instance, the addition of 2 equiv of (4-phenylbutyl)amine to 1,1′-formylferrocene followed by reduction with NaBH(OAc)$_3$ led to a mixture of the desired aminoferrocene **5** with a secondary product identified as the 2-aza[3]ferrocenophane **6**. Diluting the solution by a factor of 10 did not improve this selectivity.

2-Aza[3]ferrocenophanes with structures similar to that of **6** have been previously formed by condensation of the diol 1,1′-bis(hydroxymethyl)ferrocene with primary amines conducted at high temperature (180 °C) with RuCl$_2$(PPh$_3$)$_3$ as catalyst;[24] By this method, yields ranging from 50% to 70% have been reported. Synthetic methods of parent compounds based on the amination of 1,1′-formylferrocene have been also reported with lower yields,[25] or very long reaction times.[26] We were dissatisfied with the chemoselectivity of the reductive amination with primary amines; we thus looked for specific conditions that might exclusively lead either to 2-aza[3]ferrocenophanes (of type **6**) or to the initially targeted [(monoalkyl)-aminomethyl]ferrocenes (of type **5**). Under the mild synthetic conditions employed to produce **1** (room temperature, 18 h), the 2-aza[3]ferrocenophanes **6**−**8** (Scheme 5) have been synthesized in satisfactory 70−75% isolated yields by simply adjusting the amount of primary amine to 1 equiv of ferrocenedicarbaldehyde; this precludes the formation of the (aminomethyl)ferrocenes. From a mechanistic view, a first *intermolecular* condensation/reduction is followed by an *intramolecular* condensation/reduction of the transitory imine and/or iminium species formed. The formation of the bridge is evidenced in ^{1}H NMR with a shielding of the protons of the methylene spacer (Cp−C*H*$_2$−N), found around 2.80 ppm for **6**−**8** in comparison to values for **1**−**4** of around 3.40 ppm (see Table 1). The bridge formation at the nitrogen atom is associated with a ^{15}N NMR signal found at 87.0 ppm for **6** and 89.2 ppm for **8**.[20] X-ray diffraction studies have been performed on the 2-aza[3]ferrocenophanes formed (Figure 4).

Ferrocenophanes **6**−**8** present very similar crystallographic structures, evidencing the three-membered CNC bridge linking the two cyclopentadienyl rings of the ferrocene. Compound **6** crystallizes in the noncentrosymmetric *Pna*2$_1$ space group, and **7** and **8** crystallize in centrosymmetric *P*2$_1$/*n* and $P\bar{1}$ space groups. Due to the aza bridge, the cyclopentadienyl rings are bent and exhibit dihedral angles (deviation from parallelism) equal to 11.76(18)° for **6**, 12.82(7)° for **7**, and 11.99(8)° for **8**. Similar geometrical features have been reported in the literature for ferrocene derivatives incorporating such [−CH$_2$−NR−CH$_2$−] bridging groups: for instance, in *N*-methyl-*N*-(benzylpropyl)-2-aza[3]ferrocenophane hexafluorophosphate and *N*-hexyl-*N*-methyl-2-azonia[3]ferrocenophane iodide.[27] Compound **8** has been very recently described with identical crystallographic characteristics.[25]

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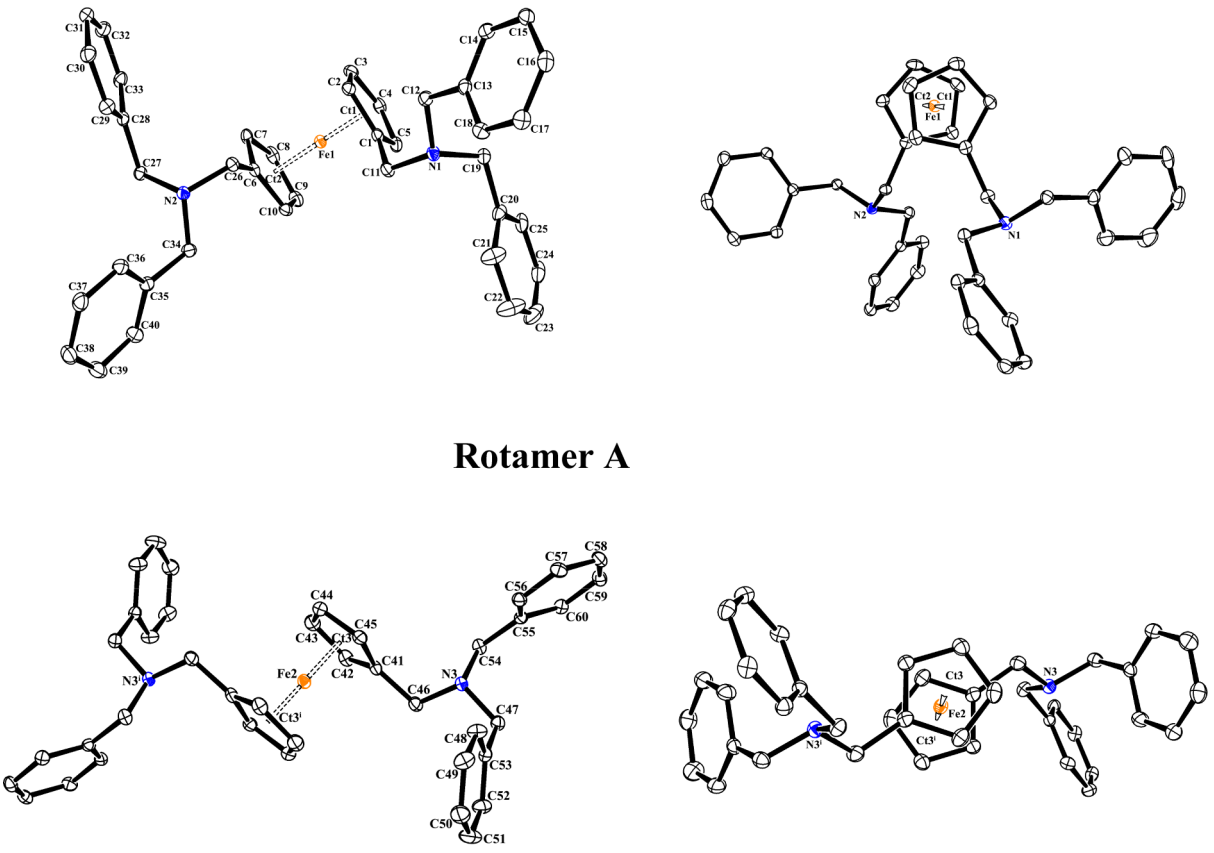
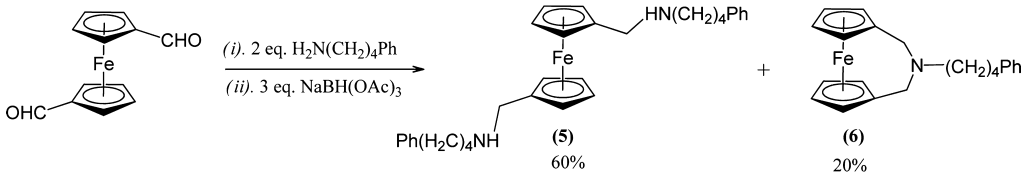
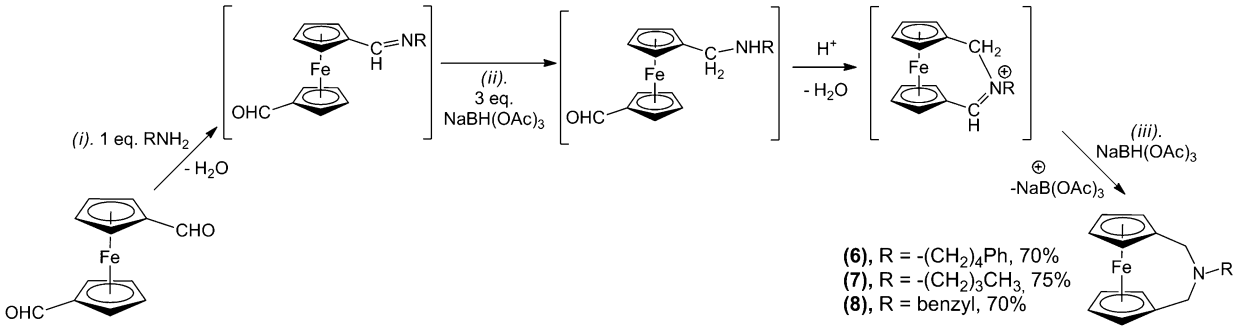


Figure 3. Molecular structure of **4** (left) and view from above (right). Hydrogen atoms are omitted for clarity. The two rotamers **A** (top) and **B** (bottom) are present in the unit cell. Selected bond lengths (Å) and angles (deg) for rotamer **A**: Fe1−Ct1 = 1.651(2), Fe1−Ct2 = 1.650(2), N1−C11 = 1.474(3), N1−C12 = 1.463(3), N1−C19 = 1.466(3), N2−C26 = 1.473(3), N2−C27 = 1.469(3), N2−C34 = 1.463(3); Ct1−Fe1−Ct2 = 179.34(11), C11−N1−C12 = 112.11(16), C11−N1−C19 = 113.09(17), C12−N1−C19 = 111.35(16), C26−N2−C27 = 113.20(15), C27−N2−C34 = 110.47(16), C26−N2−C34 = 112.90(16); C11−Ct1−Ct2−C26 = 49.22(9). Selected bond lengths (Å) and angles (deg) for rotamer **B**: Fe2−Ct3 = 1.654(2), N3−C46 = 1.466(3), N3−C47 = 1.468(3), N3−C54 = 1.459(3); C46−N3−C47 = 110.24(17), C47−N3−C54 = 111.84(17), C46−N3−C54 = 111.09(17). Symmetry transformation: (i) $-x, -y, 1 - z$.

Scheme 4. (Aminomethyl)ferrocene Derivatives from Primary Amines



Scheme 5. 2-Aza-[3]ferrocenophane from 1,1′-Formylferrocene Reacted with Primary Amines



In order to selectively form the targeted [(monoalkyl)-aminomethyl]ferrocene derivatives the experimental conditions have to be changed. First, we isolated the intermediary imine formed (Scheme 6);[28] then more drastic reduction conditions

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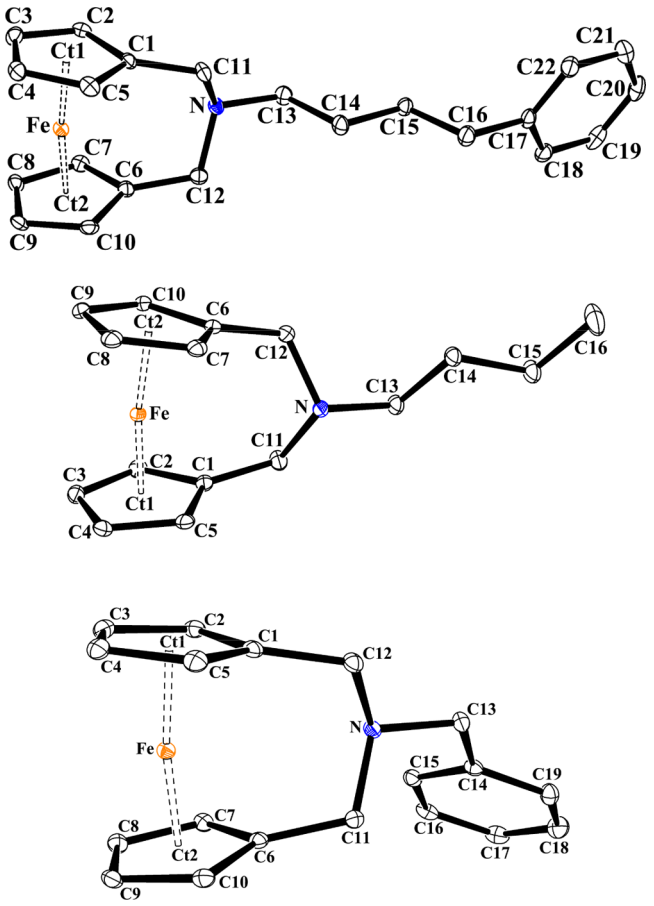


Figure 4. Molecular structures of 2-aza[3]ferrocenophanes **6** (top), **7** (middle), and **8** (bottom). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg) are as follows. For **6**: Fe−Ct1 = 1.635(3), Fe−Ct2 = 1.631(3), N−C11 = 1.471(4), N−C12 = 1.471(4), N−C13 = 1.476(5); Ct1−Fe−Ct2 = 171.57(19), C11−N−C12 = 113.5(3), C11−N−C13 = 111.1(2), C12−N−C13 = 111.6(2); C11−Ct1−Ct2−C12 = −0.70(12). For **7**: Fe−Ct1 = 1.6368(17), Fe−Ct2 = 1.6352(16), N−C11 = 1.479(2), N−C12 = 1.475(2), N−C13 = 1.478(2); Ct1−Fe−Ct2 = 170.82(9), C11−N−C12 = 111.04(14), C11−N−C13 = 107.64(13), C12−N−C13 = 110.25(13); C11−Ct1−Ct2−C12 = 1.89(7). For **8**: Fe−Ct1 = 1.6350(13), Fe−Ct2 = 1.6355(13), N−C11 = 1.4757(16), N−C12 = 1.4769(16), N−C13 = 1.4679(16); Ct1−Fe−Ct2 = 171.25(6), C11−N−C12 = 111.78(10), C11−N−C13 = 109.78(10), C12−N−C13 = 110.10(10); C12−Ct1−Ct2−C11 = 1.22(5).

were applied by using $LiAlH_4$ on imines in highly dilute THF solution. Following this procedure ferrocenylimines **9** and **11** were isolated in excellent yield and their reduction led to [(alkyl)aminomethyl]ferrocenes **10** and **12** in high yield. In this way the concomitant formation of *ansa*-ferrocene was fully circumvented. In our hands the ((*N*-alkylimino)methyl)-ferrocenes **9** and **11** were obtained as oily brown products respectively characterized in ^{1}H NMR by their N=C*H* protons at 7.98 and 8.02 ppm and in ^{13}C NMR by their corresponding signals at 159.8 ppm. Despite repeated efforts, ^{15}N NMR of imino compounds was unsuccessful due to magnetization transfer problems between protons and nitrogen.

The reduction of the imine function of **9** and **11** is quantitative and provides compounds **10** and **12**, respectively. These secondary amines were characterized in ^{1}H NMR by their H−N protons at 1.09 and 1.15 ppm and in ^{15}N NMR by their corresponding signals at 71.5 and 95.7 ppm, respectively. As for compound **2**,[22] it is also tempting here to associate the low-field chemical shift of 95.7 ppm found for **12** with steric reasons rather than electronic reasons. Indeed, as shown by X-ray diffraction (Figure 5), the tetrahedral deformation at

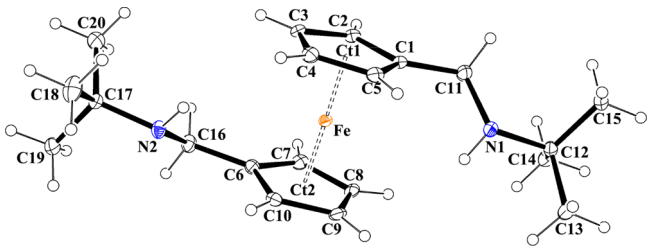
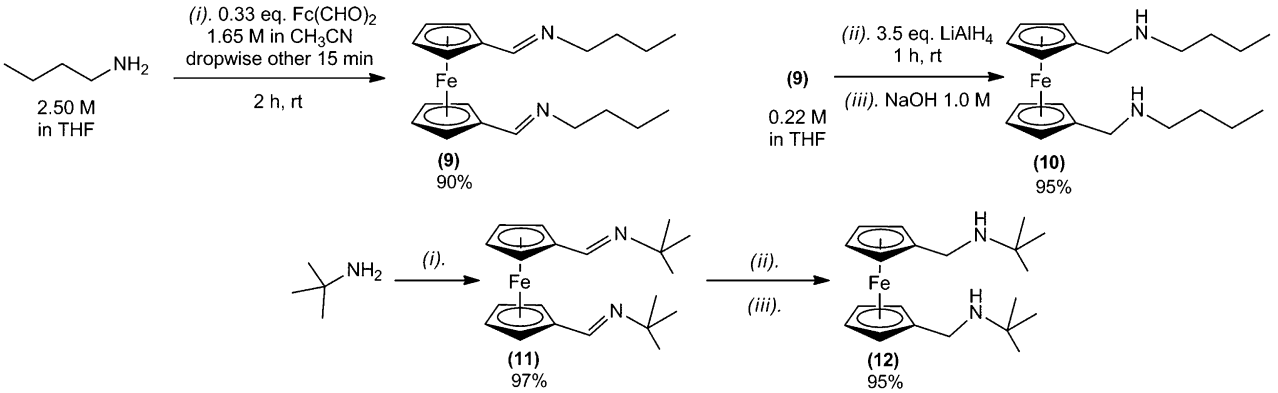


Figure 5. Molecular structure of 1,1′-bis(*N*-(*tert*-butyl)amino)-methyl)ferrocene (**12**). Selected bond lengths (Å) and angles (deg): Fe1−Ct1 = 1.656 (2), Fe1−Ct2 = 1.655(2), N1−C11: = 1.460(3), N1−C12 = 1.483(3), N2−C16 = 1.451(3), N2−C17 = 1.483(3); C11−N1−C12 = 116.72(18), C16−N2−C17 = 117.77(17), Ct1−Fe−Ct2 = 177.76(11); C11−Ct1−Ct2−C16 = −155.22(9).

nitrogen is marked in comparison to other derivatives presented herein with angles C11−N1−C12 = 116.72(18)° and C16−N2−C17 = 117.77(17)°, while mostly values between 109 and 114° have been found for **3**, **4**, **6**−**8**, and **13** (see below). Compound **12** crystallizes in the non-centrosymmetric $P2_1$ group with an almost eclipsed conformation for the cyclopentadienyl rings, in which the two (*tert*-butylamino)methyl groups are in *trans* positions with the

Scheme 6. Two-Step Selective Synthesis of [(Alkyl)aminomethyl]ferrocenes 10 and 12 from 1,1′-Formylferrocene, via Ferrocenylimines 9 and 11



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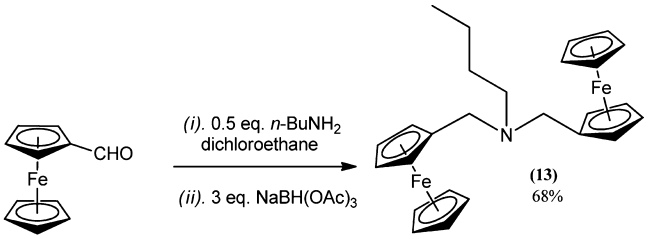
torsion angle C11−Ct1−Ct2−C16 = −155.22(9)°. The molecule belongs to the C_2 point group (noncrystallographic axis).

The ferrocene compounds **1**−**12** all combine a single ferrocene platform with either two or one nitrogen-containing moiety (Scheme 2). We envisioned that a complementary structure accessible from primary amines would combine two ferrocene moieties on an amine platform (Scheme 7), possibly leading to different properties, in particular regarding electrochemical behavior.

Scheme 7. *N,N*-Bis((ferrocenyl)methyl)-*N*-butylamine (13)



The reaction of 2 equiv of formylferrocene with *n*-butylamine followed by reductive amination with $NaBH(OAc)_3$ led to the formation of *N,N*-bis((ferrocenyl)methyl)-*N*-butylamine (**13**), which was isolated in a satisfactory 68% yield. The compound was characterized in ^1H and ^{13}C NMR by the intense signals found respectively at 4.01 and 68.5 ppm due to the unsubstituted H−C of cyclopentadienyl rings. The chemical shift for **13** in ^{15}N NMR found at 76.8 ppm is very similar to that of **1**, probably due to their analogous connection framework around nitrogen. The X-ray structure of **13** was resolved (Figure 6), which confirmed that the amine group connects two ferrocene moieties. This compound crystallizes in the centrosymmetric $P2_1/c$ group with ferrocenyl moieties positioned *exo* to each other and the nitrogen atom placed in a fairly regular environment with C21−N−C22 = 111.2(3)°, C21−N−C23 = 110.4(3)°, C22−N−C23 = 112.9(3)°, and N−C distances around 1.47−1.48 Å. An interesting, but intractable, compound having a structural analogy with **13** has been fortuitously formed from zinc-promoted rearrangement of an (aminomethyl)ferrocene derivative.[29] Our present methodology is thus a straightforward way to produce this kind of unusual structure from RNH_2 amine precursors.

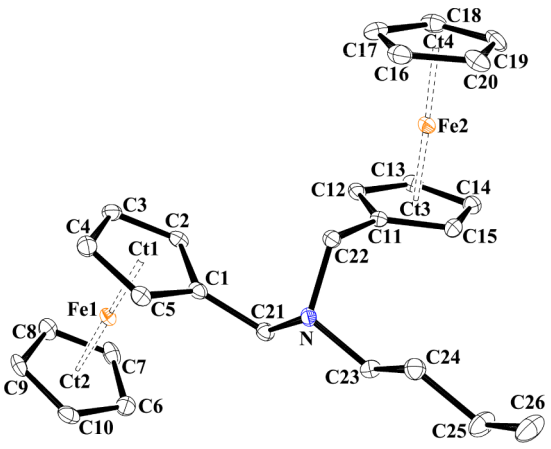


Figure 6. Molecular structure of *N,N*-bis((ferrocenyl)methyl)-*N*-butylamine (**13**). Hydrogen atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Fe1−Ct1 = 1.647(4), Fe1−Ct2 = 1.648(5), Fe2−Ct3 = 1.649(4), Fe2−Ct4 = 1.651(5), N−C21 = 1.473(6), N−C22 = 1.485(5), N−C23 = 1.477(6); C21−N−C22 = 111.2(3), C21−N−C23 = 110.4(3), C22−N−C23 = 112.9(3), Ct1−Fe1−Ct2 = 178.9(2), Ct3−Fe2−Ct4 = 178.3(3).

Electroanalytical Studies. Substituted ferrocene molecules are able to lose one electron (Fe(II) → Fe(III)) at potentials that are a function of the electron-donating ability of the substituents attached to the cyclopentadienyl rings, without experiencing fragmentation of their metallocenic backbone.[1] This property constitutes a useful characterization of the influence of these pendant fragments. Additionally, in the case of the novel (aminomethyl)ferrocene derivatives prepared herein the electrochemical behavior of the nitrogen-containing moiety is also of interest. Electrochemical studies reported with ligand molecules parent to those synthesized herein have been proved to be of fundamental interest to assess, from their coordination chemistry, their potential as redox sensors toward various transition-metal cations.[30] We conducted comparative electrochemical analyses on a selection of ferrocenes representative of the different families developed herein (see Scheme 2). Thus, the cyclovoltammetric behavior (CV) of **2**−**4**, **7**, **8**, **10**, and **13** was investigated in dichloromethane with 0.2 mol/L NBu_4PF_6 as supporting electrolyte. These conditions are well-suited for studies in anodic electrochemistry, as they provide a large potential window in the positive range. Additionally, this medium is poorly nucleophilic, thus minimizing the possibility of interference in the electrode process.

Among the series of (aminomethyl)ferrocenes **1**−**4**, compound **3** is a representative example: its CV recorded at 100 mV/s is displayed in Figure 7 (top left). Two well-separated oxidations occur at, respectively, −0.01 and 0.73 V vs Fc^+/Fc^0 (see Table 2). These potential values are indicative of the electron transfer operating successively on the Fe(II) center[31] and on the amino function.[32]

Figure 7 (top right) also presents the CV of **3** obtained when the potential scan is restricted to the ferrocenyl oxidation zone. The response fulfills the characteristics of a one-electron fast electron transfer:[34] i.e., a separation between the forward anodic and backward cathodic peak ($\Delta E_p = E_{pa} - E_{pc}$) approaching 58 mV (found experimentally at 74 mV) and a difference between the half-peak and peak potentials $E_{pa} - E_{pa/2}$ near 55 mV (found experimentally at 57 mV). Additionally, the current peak i_{pa} grows proportionally to $v^{1/2}$ in accordance with a diffusion-controlled process, and a ratio of peak currents close to unity is observed (experimental: $i_{pc}/i_{pa} = 0.84$).[35]

As shown in Figure 7 (top left), when the potential scan is extended to +1.32 V, an oxidation peak related to the amine moiety appears (O2 peak). This corresponds to an electrochemically irreversible phenomenon with no associated cathodic peak at the same potential on the reverse scan. On the other hand, the reverse scan displays a fairly intense peak arising at +0.39 V (R2*). This evolution evidences a chemical reaction occurring on the (aminomethyl)ferrocene after the oxidation electron transfer; the product of this reaction is then reduced, and this corresponds to peak R2*. Such a cascade process may be related to anodic reactions of aliphatic tertiary amines containing acidic hydrogen atoms in the α position (Scheme 8). The reaction pathway proceeds through the intermediacy of a nitrogen-centered radical cation which is deprotonated and further oxidized to an iminium ion.[32] Eventually, the iminium can be hydrolyzed by traces of water

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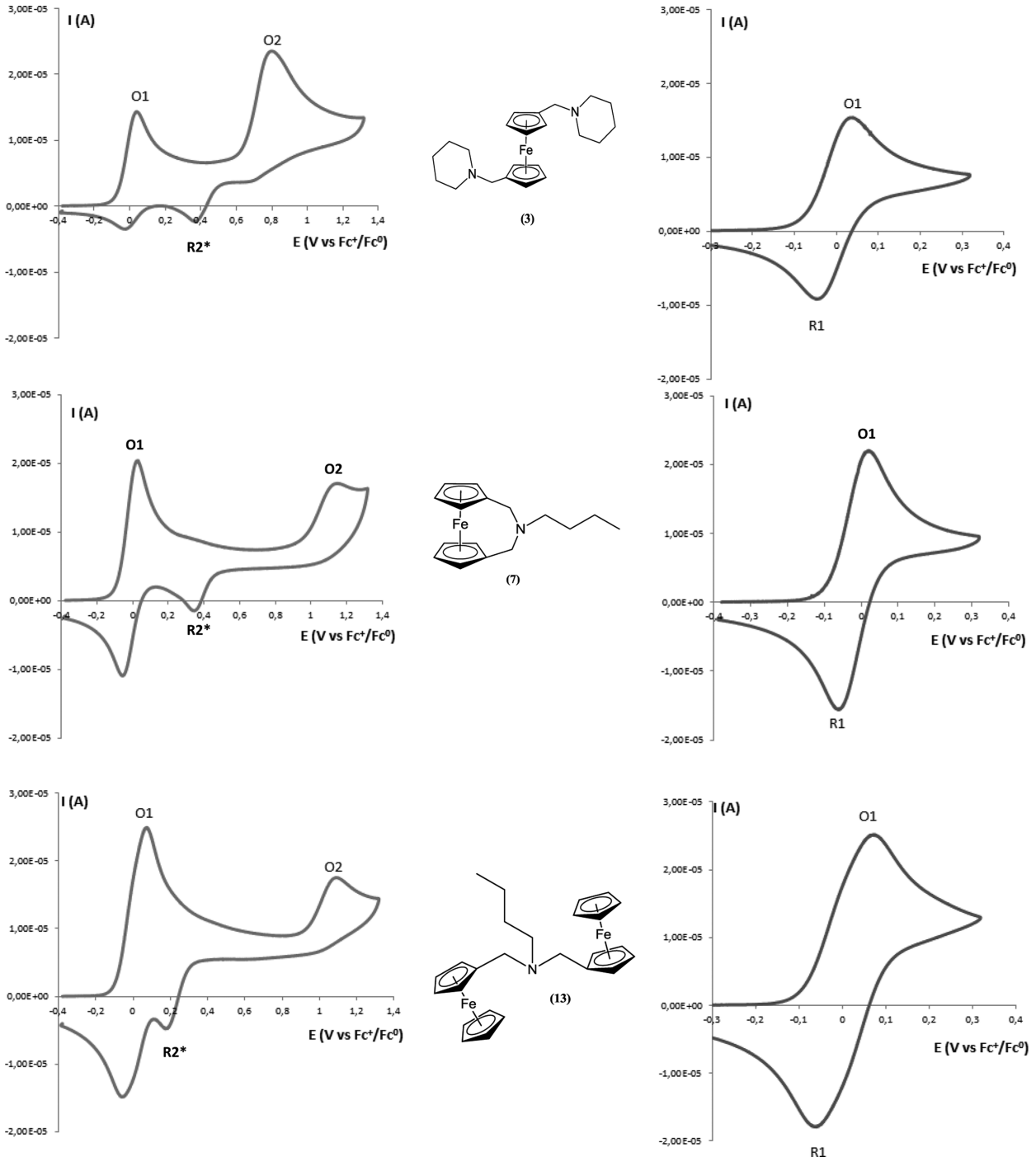

Figure 7. Cyclic voltammograms of complexes **3** (top), **7** (middle), and **13** (bottom) in CH_2Cl_2/0.2 mol L^{-1} NBu_4PF_6. Working electrode: platinum disk (Φ = 1 mm). Potential scan rate: 100 mV/s. Inversion potential: 1.32 V (left) and 0.32 V (right).

Scheme 8. Electroinduced Cascade Reaction from Oxidation of a Tertiary Aliphatic Amine

$$R_1\text{-}CH_2\text{-}NR_2 \underset{+\,e^-}{\overset{-\,e^-}{\rightleftharpoons}} R_1\text{-}CH_2\text{-}\overset{\cdot+}{N}R_2 \xrightarrow{-\,H^+} R_1\text{-}\dot{C}H\text{-}NR_2 \underset{+\,e^-}{\overset{-\,e^-}{\rightleftharpoons}} R_1\text{-}CH{=}\overset{\oplus}{N}R_2 \xrightarrow{H_2O} \begin{matrix} R_1\text{-}CH{=}O \\ + \\ HNR_2 \end{matrix}$$

to yield the corresponding aldehyde and secondary amine (Scheme 8).

In addition, the H^+ liberated in the reaction sequence is able to protonate the starting amine to form an electroinactive ammonium species (Scheme 9).

The reactivity depicted in Schemes 8 and 9 may be transposed in the anodic reaction of **3**, potentially leading to the formation of ferrocenium derivatives **3a**–**c** (Scheme 10). The formation of **3a** would then results from the deprotonation of the methylene group in the lateral chain of **3**; the proton acidity at this position is indeed expected to increase due to the proximity of the positively charged ferrocenium. Protonation and/or hydrolysis reactions of the formed ferroceniums (as

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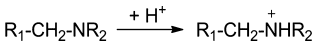
Table 2. Cyclic Voltammetry of Ferrocene Derivatives 2−4, 7, 8, 10, and 13[a]

	first oxidation step					second oxidation step
compd	$E_{1/2}$ (V)[b]	ΔE_p (mV)[c]	$E_p - E_{p/2}$ (mV)	$\lvert i_{pa}/i_{pc}\rvert$	σ_p[d]	E_p (V)
2	0.02[e]		69			0.73
3	−0.01	74	57	0.84	−0.11	0.79
4	−0.01	65	56	0.92	−0.11	1.07
7	−0.03	73	56	0.92	−0.13	1.14
8[f]	−0.03	76	50	0.93	−0.13	1.24
10	0.00[e]		75			[g]
13	−0.04, 0.03[h]	129	92			1.08

[a]Experimental conditions: working electrode material, platinum; sweep rate, 100 mV/s; all potentials referenced to the Fc^+/Fc^0 couple, 0.2 mol/L NBu_4PF_6 in CH_2Cl_2; uncompensated resistance R_u not taken into account.[33] [b]Calculated as the half-sum of E_{pa} and E_{pc} at the first oxidation step. [c]Calculated as the difference between E_{pa} and E_{pc}. [d]σ_p is the Hammett parameter for the substituent on Cp. [e]Peak O1 is chemically irreversible: E_{pa} is given as a substitute for $E_{1/2}$. [f]The electrochemistry of this compound was previously described:[24,27] our data are included for appropriate comparison within the whole series. [g]Not observed clearly. [h]$E_{1/2}$ identified to the formal potential, $E°$, obtained by numeric simulation (see the Supporting Information).

Scheme 9



described above for amines and iminiums, respectively) may also occur.

Accordingly, the peak R2* in the CV of **3** (Figure 7, top) is associated with the $Fe^{III} \rightarrow Fe^{II}$ reduction of one or several of these compounds. The more positive potential of R2* in comparison to R1 in the compounds is attributable to the substituents on the Cp rings. They are expected to exert an electroattractive effect on ferrocenium. To definitively attribute peak R2*, the ammonium form of **3** (**3**·2H$^+$) as well as the 1,1′-diformylferrocene have been analyzed in cyclic voltammetry. Both display a unique electrochemically reversible one-electron oxidation in the accessible potential range, thus generating **3b,c** (Scheme 10) at the electrode, respectively. The corresponding reduction peak is different from R2* (potential at 0.39 V) with values found at 0.30 and 0.58 V, respectively. Therefore, R2* could be the trace associated with **3a** (Scheme 10) with consistently a potential fairly close to **3b**.

The other ferrocene derivatives **2**−**4**, **7**, **8**, **10**, and **13** were analyzed under the same conditions (see Table 2). These species have an electroanalytical behavior roughly similar to that of **3** with two net oxidation peaks present at potentials in accordance with anodic reactions respectively occurring at the iron center and methylamine moieties. At 100 mV/s, the first oxidation (peak O1) is also reversible in the case of **4**, **7**, and **8** (see the characteristic parameters in Table 2) but chemically irreversible in the case of **2** and **10**. Only minor variations are noted in the half-wave potentials, which are fixed at either −0.01 or −0.03 V. Bridged 2-azaferrocenophanes have the most negative $E_{1/2}$ values (**7** and **8**, Table 2). This shift is limited in magnitude to −30 mV in comparison to the mean value of the nonbridged compounds ($E_{1/2}$ = 0.00 V from **2**, **3**, **4**, and **10**). This differs from previous comparisons between ferrocene derivatives having three bridging atoms and their nonbridged analogues,[31] comparisons for which the bridged compound was generally stabilized with accordingly a more positive $E_{1/2}$.

The Hammet parameter, σ_p, for the substituent on cyclopentadienyl rings can be extracted from the relationships (1) and (2):[31]

$$E_L(\text{vs NHE}) = {}^1/_2[E_{1/2}(\text{vs } Fc^+/Fc^0) + 0.63] \quad (1)$$

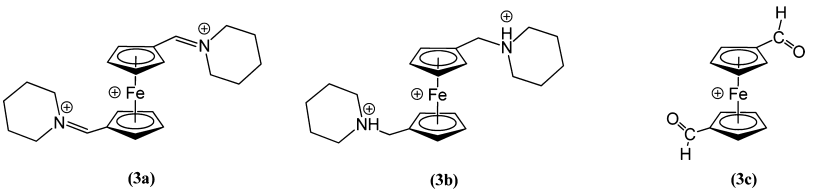
$$E_L = 0.45\sigma_p + 0.36 \quad (2)$$

The σ_p values obtained range between −0.13 and −0.11, which confirms a weak electrodonating effect from aminomethyl to Cp. In comparison, the σ_p value estimated for the ferrocene bearing an electron-rich 2,5-dimethylpyrrolidin-1-yl group directly attached to the cyclopentadienyl ring was found to be −1.03.[36]

While all the compounds reported herein combine ferrocenyl and nitrogen-containing groups, the ratio of the two entities changes in the series. Hence, compounds **2**−**4** and **10** incorporate a single ferrocene and two amine moieties (tertiary, or secondary for **10**); conversely **7** and **8** combine a ferrocene with a single bridging tertiary amine, and finally compound **13** connects two ferrocenyl moieties via one tertiary amine. The influence of these structural differences is easily evidenced by comparison of the cyclic voltammograms of, for instance, **3**, **7** and **13** (Figure 7), for which the relative intensity of O2 vs O1 is found to be as follows: **3** > **7** > **13**.

A careful examination of the short potential scan CV of **13** (Figure 7, bottom right) reveals that the observed trace results from the sum of two closely spaced one-electron systems. Digital simulation of the CV response has allowed extraction of the respective formal potentials of the two ferrocene derivative systems (Table 2).[37] A molecule bearing two independent and chemically equivalent redox centers should theoretically exhibit a $\Delta E°$ value equal to 35.6 mV.[38] The separation of 72.0 mV observed in the case of **13** is clearly indicative of a certain extent of electronic "communication" between the two electroactive iron centers. This communication might occur through space as a result of the electrostatic repulsion between electrogenerated charges or internally through the 2-azopropylene bridge. Analogous electrochemical signatures have been described for molecules accommodating two ferrocenyl groups connected via a conjugated π system.[39]

Scheme 10



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CONCLUSION

Aminomethyl-substituted ferrocenes are key building blocks applied, for instance, in the synthesis of efficient bioactive compounds and as platforms for further synthesizing *ortho*-substituted ferrocenes. However, for these compounds more efficient synthetic modes and structural diversification are needed. This has been achieved herein especially by reducing the number of synthetic steps, by getting better yields and selectivity, and also by the introduction of amino groups other than the classical aliphatic alkyl amines $-NMe_2$ and $-NEt_2$. We optimized the straightforward syntheses of a variety of 13 aminomethyl-substituted ferrocenes (giving either tertiary amines **1**−**4** or secondary amines **5**, **10**, and **12**) and the parent compounds (iminomethyl)ferrocenes (**9**, **11**), azaferrocenophanes (**6**−**8**), and a diferrocenylamine (**13**). Compounds **1**−**13** are obtained in two or three synthetic steps (in 65−97% yield) from ferrocene via the reductive amination of 1,1′-diformylferrocene or formylferrocene. Depending on the targeted ferrocene derivatives, the choice of $NaBH(OAc)_3$ or $LiAlH_4$ as reducing agent was determining for the selectivity of the reaction. ^{15}N NMR measurements of aminomethyl-substituted ferrocenes and derivatives are provided for the first time, establishing benchmark values ranging from 71.5 to 95.7 ppm. For representative compounds the characterization has been extended to X-ray diffraction structures, evidencing the preferential conformation of ferrocene backbones, and also to electrochemical analysis, in which two very distinct oxidations occur, indicative of the electron transfer operating successively on the Fe(II) center and on the amino function. The synthesis of (aminomethyl)ferrocene derivatives is part of a research program for the synthesis and study of new (N,X)-substituted ferrocenes, and further works will aim at their *ortho*-directed functionalization.

EXPERIMENTAL SECTION

General Procedures. The reactions were carried out in oven-dried glassware (115 °C) under an argon atmosphere using Schlenk and vacuum-line techniques. Solvents were dried and freshly distilled prior to use by standard methods. All the chemicals were used as supplied, without further purification. 1,1′-Diformylferrocene was prepared from ferrocene according a slightly modified reported procedure.[40] Amines from commercial sources were used. Sodium triacetoxyborohydride reducing agent was stored under argon. Flash chromatography was performed on silica gel (220−440 mesh). The identity and purity of the products were established at the "*Chemical Analysis platform and Molecular Synthesis University of Burgundy*" using high-resolution mass spectrometry, multinuclear NMR, and elemental analysis. The exact masses were obtained from a LTQ-Orbitrap XL (THERMO). ^1H (300.13, 500.13, or 600.13 MHz) and ^{13}C NMR spectra (75.5, 125.8, or 150.9 MHz) (δ in ppm) were recorded in $CDCl_3$ at 298 K (unless otherwise stated) on a Bruker 300 Avance, Bruker 500 Avance DRX, or Bruker 600 Avance II spectrometer. Elemental analysis was performed on an Analyzer CHNS/O Thermo Electron Flash EA 1112 Series. The ^{15}N NMR chemical shifts measured by $^1H-^{15}N$ heteronuclear multiple-bond correlation spectroscopy (HMBC) were recorded in $CDCl_3$ at 300 K on a Bruker Avance II 600 MHz spectrometer with a BBI 5 mm probe. Neat nitromethane has been used as an external standard reference, for which the ^{15}N chemical shift is taken to be 0 ppm.

X-ray Structure Analysis. X-ray analyses of compounds **2**−**4**, **6**−**8**, **12**, and **13** were achieved from intensity data collected on a Nonius Kappa CCD instrument at 115 K. The structures were solved by direct methods (SIR92)[41] and refined with full-matrix least-squares methods based on F^2 (SHELXL-97)[42] with the aid of the WINGX program.[43] All non-hydrogen atoms were refined with anisotropic thermal parameters. Hydrogen atoms attached to carbon atoms were included in calculated positions and refined as riding atoms. Crystallographic data are reported in the Supporting Information.

Electrochemical Analysis. All electrochemical measurements were carried out in a standard three-electrode glass cell under an inert atmosphere of dry oxygen-free argon. A double-junction saturated calomel electrode—with background electrolyte between two frits—was used as the reference electrode. The formal potential of the $[Fc^+/Fc]$ couple was found to be 0.38 V in 0.2 M $[NBu_4][PF_6]/CH_2Cl_2$ media vs SCE. Cyclic voltammograms were registered with the use of a PGSTAT302N potentiostat (Autolab-Ecochemie). A well-polished platinum disk (1 mm diameter) served as working electrode. Platinum wire was used as the counter electrode. Digital simulation of the cyclic voltammogram for **13** was achieved with the commercial software DIGISIM 3.05 (Bioanalytical Systems). For the synthesis of $[NBu_4][PF_6]$, tetra-*n*-butylammonium hydroxide (Alfa-Aesar, 40% w/w aqueous solution) was mixed with a stoichiometric amount of HPF_6 (Sigma Aldrich, 65% w/w aqueous solution). The obtained salt was crystallized three times from ethanol and kept in an oven at 80 °C for several days. Copies of cyclic voltammograms are available upon request to the authors.

Synthesis of 1,1′-Diformylferrocene and Formylferrocene. To a vigorously stirred mixture of degassed ferrocene (2.0 g, 10.75 mmol) with 3.54 mL of tetramethylethylenediamine (TMEDA) cooled to 0 °C (2.2 equiv, 23.65 mmol) was added dropwise 14.8 mL of a 1.6 M solution of *n*-butyllithium in hexane cooled to −80 °C, over 15 min (2.2 equiv, 23.65 mmol). The mixture was then stirred at room temperature overnight. The mixture was filtered, and the solid was rinsed with heptane. The resulting solid in 20 mL of heptane was cooled to −80 °C, and the dropwise addition of 1.8 mL of DMF was conducted (2.2 equiv, 23.65 mmol). The mixture was stirred at −80 °C for 2 h, hydrolyzed with 10 mL of H_2O, then extracted with CH_2Cl_2. The combined organic phases were dried on $MgSO_4$, and the solvent was removed in vacuo. From SiO_2 column chromatography a first fraction of unreacted ferrocene (<10%) is eluted with pure heptane, then with a 1/1 EtOAc/heptane mixture, formylferrocene is obtained (0.34 g, 2.1 mmol, 20% yield), and finally elution with pure EtOAc gives 1,1′-diformylferrocene as a bright red crystalline solid after evaporation of this third fraction (yield 71%, 3.7 g, 15.28 mmol). Due to our interest in formylferrocene as a reagent for our investigation, we did not conduct optimization of the yield of 1,1′-diformylferrocene.[44] 1,1′-Diformylferrocene: ^1H NMR δ 9.94 (s, 2H, C*H*O), 4.88 (pt, 4H, α-Cp-C*H*), 4.66 (pt, 4H, β-Cp-C*H*); $^{13}C\{^1H\}$ NMR δ 192.9 (s, 2C, CHO), 80.7 (s, 2C, *ipso*-Cp), 74.3 (s, 4C, α-Cp-CH), 70.87 (s, 4C, β-Cp-CH); HR-MS ($C_{12}H_{10}O_2Fe$) ESI [M + Na^+] *m*/*z* calcd 264.9916, found 264.9922, [err] 2.426 ppm. Anal. Calcd for $C_{12}H_{10}O_2Fe$ (242.05): C, 59.54; H, 4.16. Found: C, 59.48; H, 4.38. Formylferrocene: ^1H NMR δ 9.95 (s, H, C*H*O), 4.79 (s, 2H, α-Cp-CH), 4.60 (s, 2H, β-Cp-CH), 4.27 (s, 5H, Cp); $^{13}C\{^1H\}$ NMR δ 193.4 (s, 1C, CHO), 79.4 (s, 1C, 1-Cp), 73.1 (s, 2C, α-Cp-CH), 69.6 (s, 7C, 2β-Cp-CH + 5C-Cp′-CH). Anal. Calcd for $C_{11}H_{10}FeO$ (214.04): C, 61.73; H, 4.71; Found: C, 61.41; H, 4.38.

1,1′-Bis((*N*,*N*-diethylamino)methyl)ferrocene (1). To a solution of 1,1′-diformylferrocene (0.53 g, 2.18 mmol) in dichloroethane (30 mL) was added diethylamine (2.0 equiv, 0.45 mL, 4.36 mmol), and the mixture was stirred for 1 h at room temperature. To this suspension was added 1.38 g of sodium triacetoxyborohydride (3 equiv, 6.54 mmol). The mixture was stirred at room temperature overnight. The reaction mixture was hydrolyzed by addition of 1 M NaOH (20 mL), the phases were separated, and the aqueous phase was extracted with CH_2Cl_2 (3 × 30 mL). The combined organic phases were dried on $MgSO_4$, and the solvents were removed in vacuo. Column chromatography on SiO_2 using CH_2Cl_2/MeOH/triethylamine (90:9:1) gave 1,1′-bis((*N*,*N*-diethylamino)methyl)ferrocene as a red oily product in 97% yield after solvent evaporation (0.75 g, 2.10 mmol). ^1H NMR: δ 1.02 (t, 12H, J_{HH} = 7 Hz, CH_2CH_3), 2.43 (q, 8H, J_{HH} = 7 Hz, CH_2CH_3), 3.48 (s, 4H, Cp-CH_2-N), 4.05, 4.08 (m (AA′BB′), 4H each, Cp-C*H*). $^{13}C\{^1H\}$ NMR: δ 12.1 (s, 4C, CH_2CH_3), 46.5 (s, 4C, CH_2CH_3), 52.2 (s, 2C, Cp-CH_2−N), 68.7 (s, 4C, 3,4-Cp), 71.7 (s, 4C, 2,5-Cp), 83.4 (s, 2C, 1-Cp). ^{15}N NMR: δ

dx.doi.org/10.1021/om400317s | *Organometallics* XXXX, XXX, XXX−XXX

76.0. HR-MS ($C_{20}H_{33}N_2Fe$) ESI: [M + H$^+$] m/z calcd 357.1987, found 357.1997, [err] 2.722 ppm. Elemental analyses were unsatisfactory (oily product).

1,1′-Bis((pyrrolidin-1-yl)methyl)ferrocene (2). To a solution of 1,1′-diformylferrocene (1.00 g, 4.13 mmol) in dichloroethane (30 mL) was added pyrrolidine (2.3 equiv, 0.89 mL, 9.5 mmol), and the mixture was stirred for 1 h. To this suspension was added 2.01 g of sodium triacetoxyborohydride (2.3 equiv, 9.5 mmol). The mixture was stirred at room temperature overnight. The reaction mixture was hydrolyzed by addition of 1 M NaOH (20 mL), the phases were separated, and the aqueous phase was extracted with CH_2Cl_2 (3 × 30 mL). The combined organic phases were dried on $MgSO_4$ and the solvents removed in vacuo. Silica gel was deactivated by pouring it into 60 mL of heptane in the presence of 10% NEt_3, followed by drying in vacuo. Column chromatography on deactivated SiO_2 using heptane/ethyl acetate (4/1) followed by heptane/ethyl acetate (3/2) gave as a second fraction 1,1′-bis((pyrrolidin-1-yl)methyl)ferrocene as a reddish crystalline solid in 65% yield after solvent evaporation (0.94 g, 2.66 mmol). Orange-yellow single crystals suitable for X-ray diffraction studies were obtained from a concentrated solution in heptane kept at −30 °C. ^{1}H NMR: δ 1.72 (quintet, 8H, $^3J_{HH}$ = 4 Hz, py-β-N-CH_2), 2.47 (quintet, 8H, $^3J_{HH}$ = 4 Hz, py-α-N-CH_2), 3.43 (s, 4H, Cp-CH_2-N), 4.05, 4.12 (m (AA′BB′), 4H each, Cp-CH). ^{13}C{^{1}H} NMR: δ 23.3 (s, 4C, py-β-N-CH_2), 53.5 (s, 4C, py-α-N-CH_2), 55.1 (s, 2C, Cp-CH_2-N), 68.6 (s, 4C, 3,4-Cp), 70.4 (s, 4C, 2,5-Cp), 83.9 (s, 2C, 1-Cp). ^{15}N NMR: δ 86.0. HR-MS ($C_{20}H_{28}FeN_2$) ESI: [M + H$^+$] m/z calcd 353.16748, found 353.16763, [err] 0.460 ppm. Anal. Calcd for $C_{20}H_{28}FeN_2$ (352.29): C, 68.19; H, 8.01; N, 7.95. Found: C, 68.58; H, 7.95; N, 7.91.

1,1′-Bis((piperidin-1-yl)methyl)ferrocene (3). To a solution of 1,1′-diformylferrocene (1.00 g, 4.13 mmol) in dichloroethane (30 mL) was added piperidine (2.3 equiv, 0.94 mL, 9.5 mmol), and the mixture was stirred for 1 h. To this suspension was added 2.01 g of sodium triacetoxyborohydride (2.3 equiv, 9.5 mmol). The mixture was stirred at room temperature overnight. The reaction mixture was hydrolyzed by addition of 1 M NaOH (20 mL), the phases were separated, and the aqueous phase was extracted with CH_2Cl_2 (3 × 30 mL). The combined organic phases were dried on $MgSO_4$, and the solvents were removed in vacuo. Silica gel was deactivated by pouring it into 80 mL of heptane in the presence of 10% NEt_3, followed by drying in vacuo. Column chromatography on deactivated SiO_2 using heptane/ethyl acetate (7/3) followed by heptane/ethyl acetate/methanol (15/10/1, with a gradual increase of ethyl acetate/methanol), gave in the second fraction 1,1′-bis((pyrrolidin-1-yl)methyl)ferrocene as a brown solid in 74% yield after solvent evaporation (1.17 g, 3.07 mmol). Brown single crystals suitable for X-ray diffraction studies were obtained from a concentrated solution in pentane kept at −30 °C. ^{1}H NMR: δ 1.35 (m, 4H, pip-γ-N-CH_2), 1.52 (m, 8H, pip-β-N-CH_2), 2.31 (m, 8H, pip-α-N-CH_2), 3.33 (s, 4H, Cp-CH_2-N), 4.04, 4.08 (m (AA′BB′), 4H each, Cp-CH). ^{13}C{^{1}H} NMR: δ 24.2 (s, 2C, pip-γ-N-CH_2), 25.8 (s, 4C, pip-β-N-CH_2), 53.7 (s, 4C, pip-α-N-CH_2), 58.8 (s, 2C, Cp-CH_2-N), 68.5 (s, 4C, 3,4-Cp), 70.9 (s, 4C, 2,5-Cp), 82.7 (s, 2C, 1-Cp). ^{15}N NMR: δ 79.0. HR-MS ($C_{22}H_{32}FeN_2$) ESI: [M + H$^+$] m/z calcd 381.19879, found 381.19898, [err] 0.557 ppm. Anal. Calcd for $C_{22}H_{32}FeN_2$ (380.35): C, 69.47; H, 8.48; N, 7.37. Found C, 69.25; H, 8.57; N, 7.08.

1,1′-Bis((*N*,*N*-dibenzylamino)methyl)ferrocene (4). To a solution of 1,1′-diformylferrocene (1.0 g, 4.13 mmol) in dichloroethane (30 mL) was added dropwise dibenzylamine (2.3 equiv, 1.82 mL, 9.5 mmol), and the mixture was stirred for 1 h at room temperature. To this suspension was added 2.01 g of sodium triacetoxyborohydride (2.3 equiv, 9.5 mmol). The mixture was stirred at room temperature overnight under argon. Then, the reaction mixture was hydrolyzed by addition of 1 M NaOH (20 mL). The phases were separated, and the aqueous phase was further extracted with CH_2Cl_2 (3 × 30 mL). The combined organic phases were dried with $MgSO_4$, and the solvents were removed in vacuo. Silica gel was deactivated by pouring it into 60 mL of heptane in the presence of 10% NEt_3, followed by drying in vacuo. Column chromatography on deactivated SiO_2 using heptane/ethyl acetate (4/1) followed by heptane/ethyl acetate/methanol (15/10/1, with a gradual increase of ethyl acetate/methanol), gave 1,1′-bis((*N*,*N*-dibenzylamino)methyl)ferrocene as a brown crystalline solid in the second fraction in 80% yield after solvent evaporation (2.0 g, 3.30 mmol). Orange-yellow single crystals suitable for X-ray diffraction studies were obtained from a concentrated solution in heptane kept at −30 °C. ^{1}H NMR: δ 3.38 (s, 4H, Cp-CH_2-N), 3.47 (s, 8H, N-CH_2-Ph), 3.96, 3.99 (m (AA′BB′), 4H each, Cp-CH), 7.26−7.36 (m, 20H, Ph-CH). ^{13}C{^{1}H} NMR: δ 52.1 (s, 2C, Cp-CH$_2$-N), 57.1 (s, 4C, N-CH$_2$-Ph), 68.4 (s, 4C, 3,4-Cp),70.6 (s, 4C, 2,5-Cp), 83.1 (s, 2C, 1-Cp), 126.7 (s, 4C, *p*-Ph-CH), 128.2 (s, 8C, *m*-Ph-CH) 128.7 (s, 8C, *o*-Ph-CH), 139.9 (s, 4C, *ipso*-Ph-*C*). ^{15}N NMR: δ 74.8. HR-MS ($C_{40}H_{40}FeN_2$) ESI: [M + Na$^+$] m/z calcd 627.24338, found 627.24152, [err] 2.858 ppm. Anal. Calcd for $C_{40}H_{40}FeN_2$ (604.60): C, 79.46; H, 6.67; N, 4.63. Found: C, 79.12; H, 6.68; N, 4.69.

1,1′-Bis(*N*-(4-phenylbutyl)amino)methyl)ferrocene (5). A procedure similar to that which was used for synthesizing **1** was employed. By reacting 0.50 g of 1,1′-diformylferrocene (2.06 mmol) and 4-phenylbutylamine (2 equiv, 0.65 mL, 4.11 mmol) in dichloroethane (30 mL), followed by treatment with sodium triacetoxyborohydride (3 equiv, 1.27 g, 6.18 mmol), **5** was obtained in 60% yield (0.60 g, 1.18 mmol) as a brown powder after column chromatographic purification to remove the *ansa* byproduct (SiO_2, CH_2Cl_2/MeOH 19/1). Alternatively, following the two-step procedure which was employed to form **10**, the (aminomethyl)ferrocene **5** was obtained in 80% overall yield. ^{1}H NMR: δ 1.58 (m, 8H, $CH_2CH_2CH_2CH_2$), 1.94 (s, broad, 2H, N*H*), 2.61 (q, 8H, J_{HH} = 7 Hz, NCH_2 + CH_2Ph), 3.52 (s, 4H, Cp-CH_2-N), 4.07, 4.13 (m (AA′BB′), 4H each, Cp-CH), 7.15−7.30 (m, 10H, Ph). ^{13}C{^{1}H} NMR: δ 29.1 (s, 2C, $CH_2CH_2CH_2$Ph), 35.80 (s, 2C each, CH_2Ph), 48.4 (s, 2C, NCH_2), 58.8 (s, 2C, Cp-CH$_2$-N), 68.7 (s, 4C, 3,4-Cp), 69.3 (s, 4C, 2,5-Cp), 85.7 (s, 2C, 1-Cp), 126.4 (s, 1C, *p*-Ph-CH), 129.1 (s, 2C, *m*-Ph-CH), 129.2 (s, 2C, *o*-Ph-CH), 142.7 (s, 1C, *ipso*-Ph-*C*). HR-MS ($C_{32}H_{40}N_2Fe$) (ESI): [M + H]$^+$ m/z calcd 509.26141, found 509.25906; [err] 4.532 ppm. Anal. Calcd for $C_{32}H_{40}N_2Fe$: C, 75.58; H, 7.93; N, 5.51. Found: C, 75.92; H, 7.32; N, 5.39.

***N*-(4-Phenylbutyl)-2-aza[3]ferrocenophane (6).** A procedure similar to that which was used for synthesizing **1** was employed. By reacting 0.50 g of 1,1′-diformylferrocene (2.06 mmol) and 4-phenylbutylamine (1 equiv, 0.30 mL, 2.06 mmol) in dichloroethane (30 mL), followed by treatment with sodium triacetoxyborohydride (3 equiv, 1.27 g, 6.18 mmol), **6** was obtained in 70% yield as a yellow powder (0.50 g, 1.39 mmol) after column chromatographic purification (SiO_2, CH_2Cl_2/MeOH 19/1). Single crystals suitable for X-ray diffraction were obtained from slow evaporation of a concentrated solution of **6** in CH_2Cl_2. ^{1}H NMR: δ 1.64, 1.74 (m, 2 H each, CH_2), 2.68 (m, 4 H, CH_2), 2.86 (s, 4H, Cp-CH_2-N), 4.04, 4.07 (m, 4 H each, Cp-CH), 7.16−7.30 (m, 5H, Ph-CH). ^{13}C{^{1}H} NMR: δ 30.2 (s, 2C, NCH$_2$CH$_2$CH$_2$), 36.6 (s, 1C, CH_2Ph), 53.0 (s, 2C, Cp-CH_2−N), 58.1 (s, 1C, NCH$_2$CH$_2$), 69.8 (s, 4C, 3,4-Cp), 70.6 (s, 4C, 2,5-Cp), 83.8 (s, 2C, 1-Cp), 126.4 (s, 1C, *p*-Ph-CH), 129.1 (s, 2C, *m*-Ph-CH), 129.2 (s, 2C, *o*-Ph-CH), 142.7 (s, 1C, *ipso*-Ph-*C*). ^{15}N NMR: δ 87.0. HR-MS ($C_{22}H_{25}FeN$) ESI: [M + H$^+$] m/z calcd 360.14094, found 360.13964, [err] 3.550 ppm. Anal. Calcd for $C_{22}H_{25}FeN$ (359.29): C, 73.54; H, 7.01; N, 3.90. Found: C, 73.37; H, 7.00; N, 3.90.

***N*-(*n*-Butyl)-2-aza[3]ferrocenophane (7).** A procedure similar to that used for synthesizing **1** was employed by reacting 0.50 g of 1,1′-diformylferrocene (2.06 mmol) and *n*-butylamine (1 equiv, 0.21 mL, 2.06 mmol) in 20 mL of dichloroethane, followed by treatment with sodium triacetoxyborohydride (3 equiv, 1.27 g, 6.18 mmol). The reaction was monitored by thin-layer chromatography and pursued until 1,1′-diformylferrocene disappeared. Then the mixture was quenched by a saturated $NaHCO_3$ solution in water and was extracted with CH_2Cl_2 (60 mL). The organic phases were dried over $MgSO_4$ and evaporated to dryness. The oily residue was purified by column chromatography on deactivated SiO_2 (by using first 4/1 and then 3/2 heptane/ethyl acetate, and at the end of the chromatography a few milliliters of methanol). This gave pure *N*-(*n*-butyl)-2-aza[3]-ferrocenophane (**7**) as a yellow solid in the second fraction in 75% yield after solvent evaporation (0.43 g, 1.52 mmol). ^{1}H NMR: δ 0.97 (t, 3H, J_{HH} = 7 Hz, CH_3), 1.42, 1.59, 2.69 (m, 2H each, CH_2), 2.89 (s,

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4H, Cp-CH_2-N), 4.08 (m (AA′BB′), 8 H, Cp-C*H*). $^{13}C\{^1H\}$ NMR: δ 14.0 (s, 1C CH_3), 20.7, 29.9, 57.5 (s, 1C each, CH_2), 52.2 (s, 2C, Cp-CH_2-N), 69.0 (s, 4C, 3,4-Cp), 69.8 (s, 4C, 2,5-Cp), 83.9 (s, 2C, 1-Cp). HR-MS ($C_{16}H_{21}FeN_2$) ESI: $[M + H^+]$ m/z calcd 284.10945, found 284.10963, [err] 0.593 ppm. Anal. Calcd for $C_{16}H_{21}FeN_2$ (283.10): C, 67.86; H, 7.47; N, 4.95. Found: C, 67.21; H, 7.89; N, 4.66.

***N*-(Benzyl)-2-aza[3]ferrocenophane (8).** The procedure used for synthesizing **7** was employed by reacting 0.33 mL of benzylamine (3.02 mmol) and 0.87 g of 1,1′-diformylferrocene (1.2 equiv, 3.60 mmol) in 20 mL of dichloroethane, followed by treatment with sodium triacetoxyborohydride (2 equiv, 1.27 g, 6.18 mmol), to give after column chromatographic purification on deactivated silica gel (heptane/ethyl acetate 4/1) the 2-aza[3]ferrocenophane **8** as a yellow solid. The solid was recrystallized from a concentrated solution in pentane kept at −30 °C. The pure product **8** was obtained in 70% yield (0.67 g, 2.11 mmol) and was suitable for X-ray diffraction analysis. ^1H NMR: δ 2.82 (s, 4H, Cp-CH_2-N), 3.77 (s, 2 H, N-CH_2-Ph), 3.99, 4.04 (m (AA′BB′), 4 H each, Cp-C*H*), 7.15−7.40 (m, 5H, Ph−C*H*). $^{13}C\{^1H\}$ NMR: δ 51.1 (s, 2C, Cp-CH_2-N), 60.9 (s, 1C, N-CH_2-Ph), 68.1 (s, 4C, 3,4-Cp), 68.8 (s, 4C, 2,5-Cp), 82.6 (s, 2C, 1-Cp), 125.9 (s, 1C, *p*-Ph-*C*H), 127.3 (s, 2C, *m*-Ph-*C*H), 127.6 (s, 2C, *o*-Ph-*C*H), 138.7 (s, 1C, *ipso*-Ph-*C*). ^{15}N NMR: δ 89.2. HR-MS ($C_{19}H_{19}FeN$) ESI: $[M + H^+]$ m/z calcd 318.09287, found 318.09398, [err] 3.453 ppm. Anal. Calcd for $C_{19}H_{19}FeN$ (317.21): C, 71.94; H, 6.04; N, 4.42. Found: C, 71.64; H, 5.91; N, 4.30.

1,1′-Bis((*N*-(*n*-butyl)amino)methyl)ferrocene (10) via 1,1′-Bis((*N*-(*n*-butyl)imino)methyl)ferrocene (9). *n*-Butylamine (2.45 mL, 24.79 mmol) was dissolved in 10 mL of dry THF (solution 2.48 M), and a solution of 2.00 g of 1,1′-diformylferrocene (0.33 equiv, 8.26 mmol) in 5 mL of dry CH_3CN (solution 1.65 M) was added dropwise with vigorous stirring over 15 min. The mixture was evaporated to dryness after 2 h of stirring at room temperature, and a brown oil was collected, washed with pentane, and dried in vacuo for 2 h to give 2.62 g of imine **9** (90% yield). ^1H NMR: δ 0.90 (t, 6H, J_{HH} = 7.0 Hz, CH_3), 1.32, 1.58, 3.39 (m, 4H each, CH_2), 4.28, 4.56 (s, 4 H each, Cp-C*H*), 7.98 (s, 2H, N=C*H*). $^{13}C\{^1H\}$ NMR: δ 13.9 (s, 2C, CH_3), 20.4, 33.0, 61.71 (s, 2C each, CH_2), 69.2 (s, 4C, 3,4-Cp), 71.2 (s, 4C, 2,5-Cp), 81.8 (s, 2C, 1-Cp), 159.8 (s, 2C, N=*C*H). ^{15}N NMR could not be obtained. HR-MS ($C_{20}H_{28}N_2Fe$) ESI: $[M + H]^+$ m/z calcd 353.16748, found 353.16656, [err] 2.570 ppm. Anal. Calcd for $C_{20}H_{28}N_2Fe$ (352.29): C, 68.19; H, 8.01; N, 7.95. Found: C, 68.39; H, 8.10; N, 7.91.

The (iminomethyl)ferrocene **9** (2.62 g, 7.44 mmol) was dissolved in 25 mL of dry THF (solution 0.22 M), and 0.95 g of finely divided $LiAlH_4$ was poured into the solution under argon (3.5 equiv, 0.025 mol). After 1 h of stirring at room temperature, a portion of pentane (20 mL) was added followed by several drops of an aqueous solution of 1 M NaOH. The suspension was filtered, and the filtrate was evaporated to give 2.51 g of (((*n*-butyl)amino)methyl)ferrocene **10** as an orange oil (95% yield). ^1H NMR: δ 0.88 (t, 6H, J_{HH} = 7.2 Hz, CH_3), 1.09 (s, broad, 2H, N*H*), 1.32, 1.44 (m, 4H each, CH_2), 2.58 (t, 4H, J_{HH} = 7.2 Hz, CH_2), 3.46 (s, 4H, Cp-CH_2-N), 4.02, 4.09 (m (AA′BB′), 4H each, Cp-C*H*). $^{13}C\{^1H\}$ NMR: δ 14.0 (s, 2C, CH_3), 20.5, 32.2, 49.0 (s, 2C each, CH_2), 49.4 (s, 2C, Cp-CH_2-N), 68.2 (s, 4C, 3,4-Cp), 68.8 (s, 4C, 2,5-Cp), 87.3 (s, 2C, 1-Cp). ^{15}N NMR: δ 71.5. HR-MS ($C_{20}H_{28}FeN_2$) ESI: $[M + H]^+$ m/z calcd 357.19720, found 357.19879, [err] 4.389 ppm. Anal. Calcd for $C_{20}H_{28}FeN_2$ (356.33): C, 67.41; H, 9.05; N, 7.86. Found: C, 67.65; H, 8.82; N, 8.16.

1,1′-Bis(*N*-(*tert*-butyl)amino)methyl)ferrocene (12) via 1,1′-Bis((*N*-(*tert*-butyl)imino)methyl)ferrocene (11). The procedure used for synthesizing **9** was employed by reacting *tert*-butylamine (1.05 mL, 10.00 mmol) dissolved in dry THF (8 mL) and a solution of 1,1′-diformylferrocene (0.80 g, 3.30 mmol) in dry CH_3CN (5 mL), to give 1.13 g of the (iminomethyl)ferrocene **11** as a light brown oil (3.20 mmol, 97% yield). ^1H NMR: δ 1.19 (s, 18H, CH_3-*t*-Bu), 4.24, 4.50 (s, 4 H each, Cp-C*H*), 8.02 (s, 2H, N=C*H*). $^{13}C\{^1H\}$ NMR: δ 29.9 (s, 6C, CH_3-*t*-Bu), 57.0 (s, 2C, CCH_3-*t*-Bu), 69.3 (s, 4C, 3,4-Cp), 71.1 (s, 4C, 2,5-Cp), 82.7 (s, 2C, 1-Cp), 154.5 (s, 2C, N=CH). ^{15}N NMR could not be obtained. HR-MS ($C_{20}H_{28}FeN_2$) ESI: $[M + H]^+$ m/z calcd 353.16748, found 353.16708, [err] 1.097 ppm. Anal. Calcd for $C_{20}H_{28}FeN_2$ (352.29): C, 68.19; H, 8.01; N, 7.95. Found: C, 64.99; H, 7.88; N, 6.78 (best values obtained to date, oily product).

Following the procedure used to form compound **10**, the (iminomethyl)ferrocene **11** (1.13 g, 3.2 mmol) in dilute solution (25 mL of THF) was reacted with $LiAlH_4$ to quantitatively give **12** as a reddish solid (1.08 g, 3.04 mmol, 95% yield). ^1H NMR: δ 1.15 (s, 18H, CH_3-*t*-Bu), 3.44 (s, 4H, Cp-CH_2-N), 4.05, 4.14 (m (AA′BB′), 4H each, Cp-C*H*), 8.02 (s, 2H, N=C*H*). $^{13}C\{^1H\}$ NMR: δ 29.1 (s, 6C, CH_3-*t*-Bu), 41.8 (s, 2C, Cp-CH_2-N), 50.5 (s, 2C, CCH_3-*t*-Bu), 68.1 (s, 4C, 3,4-Cp), 68.6 (s, 4C, 2,5-Cp), 88.4 (s, 2C, 1-Cp). ^{15}N NMR: δ 95.7. HR-MS ($C_{20}H_{32}FeN_2$) ESI: $[M + H]^+$ m/z calcd 357.19879, found 357.19798, [err] 2.205 ppm. Anal. Calcd for $C_{20}H_{32}FeN_2$ (356.33): C, 67.41; H, 9.05; N, 7.86. Found: C, 67.53; H, 8.79; N, 7.33.

***N*,*N*-Bis[(ferrocenyl)methyl]-*N*-butylamine (13).** A procedure similar to that which was used for synthesizing **1** was employed. By reacting 1,1′-diformylferrocene (1.00 g, 4.67 mmol) dissolved in 25 mL of dichloroethane with *n*-butylamine (0.5 equiv, 0.23 mL, 2.33 mmol) followed by treatment with sodium triacetoxyborohydride (2.3 equiv, 2.01 g, 9.50 mmol) and quenching by a saturated $NaHCO_3$ solution in water, bis(ferrocenyl)methylbutylamine **13** was obtained in 68% yield as an orange solid (0.74 g, 1.58 mmol) after purification by column chromatography on deactivated silica gel (eluent CH_2Cl_2/MeOH 4:/1). Orange single crystals suitable for X-ray diffraction studies were obtained from a concentrated solution in heptane kept at −30 °C. ^1H NMR: δ 0.80 (t, 3H, J_{HH} = 7 Hz, CH_3), 1.19 (m, 2H, CH_2CH_3), 1.35 (m, 2H, $CH_2CH_2CH_3$), 2.21 (t, 2H, J_{HH} = 7.5 Hz, NCH_2), 3.34 (s, 4H, Cp-CH_2-N), 4.01 (s, 10H, 1′-5′-Cp-C*H*), 4.04, 4.10 (m (AA′BB′), 4H each, 2−4-Cp-C*H*). $^{13}C\{^1H\}$ NMR: δ 14.1 (s, 1C, CH_3), 20.6 (s, 1C, CH_2CH_3), 29.3 (s, 1C, $CH_2CH_2CH_3$), 51.9 (s, 1C, NCH_2CH_2), 52.5 (s, 2C, Cp-CH_2−N), 67.7 (s, 4C, 3,4-Cp), 68.5 (s, 10C, 1′-5′-Cp), 70.2 (s, 4C, 2,5-Cp), 83.7 (s, 2C, 1-Cp). ^{15}N NMR: δ 76.8. HR-MS ($C_{26}H_{31}FeN_2$) ESI: $[M]^+$ m/z calcd 469.11505, found 469.11470, [err] 0.609 ppm. Anal. Calcd for $C_{26}H_{31}FeN_2$ (469.22): C, 66.55; H, 6.66; N, 2.29. Found: C, 66.79; H, 6.63; N, 2.44.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Tables, figures, and CIF files giving ^1H, ^{13}C, and ^{15}N NMR spectra and HR-MS analysis for **1**−**13**, crystal data and structure refinement details for **2**−**4**, **6**−**8**, **12**, and **13**, and simulation of the cyclic voltammetry response for **13**. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*J.-C.H.: e-mail, jean-cyrille.hierso@u-bourgogne.fr; fax, +33-380393682.

Author Contributions

⊥These authors contributed equally.

Notes

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