ORGANOMETALLICS

Article

Cite This: *Organometallics* XXXX, XXX, XXX−XXX

pubs.acs.org/Organometallics

# Flat and Efficient *HCNN* and *CNN* Pincer Ruthenium Catalysts for Carbonyl Compound Reduction

Steven Giboulot,[†,‡] Salvatore Baldino,[†,⊥] Maurizio Ballico,[†] Rosario Figliolia,[†] Alexander Pöthig,[§] Shuanming Zhang,[†,∥] Daniele Zuccaccia,[†] and Walter Baratta*[,†]

[†]Dipartimento DI4A, Università di Udine, Via Cotonificio 108, I-33100 Udine, Italy

[⊥]Dipartimento di Chimica, Università di Torino, Via Pietro Giuria, 7, I-10125 Torino, Italy

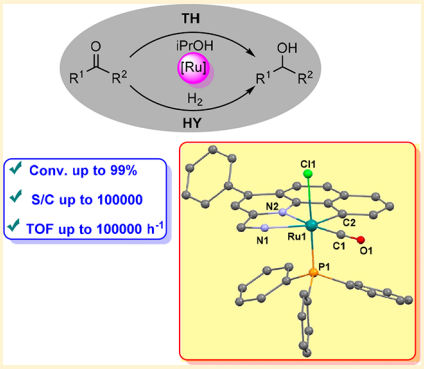
[‡]Johnson Matthey, 28 Cambridge Science Park, Milton Road, Cambridge CB4 0FP, United Kingdom

[§]Department of Chemistry & Catalysis Research Center, Technical University of Munich, Lichtenbergstraße 4, 85747 Garching, Germany

[∥]Jiangsu Industrial Technology Research Institute (JITRI), No. 699 Xuanwu Avenue, 210008 Nanjing, Jiangsu, People's Republic of China

Supporting Information

**ABSTRACT:** The bidentate HC*NN* dicarbonyl ruthenium complexes *trans,cis*-[$RuCl_2$(HC*NN*)$(CO)_2$] (**1**−**3**) and *trans,cis*-[$RuCl_2$(ampy)$(CO)_2$] (**1a**) were prepared by reaction of $[RuCl_2(CO)_2]_n$ with 1-[6-(4′-methylphenyl)pyridin-2-yl]methanamine, benzo[*h*]quinoline (HC*NN*), and 2-(aminomethyl)pyridine (ampy) ligands. Alternatively, the derivatives **1**−**3** were obtained from the reaction of $RuCl_3$ hydrate with $HCO_2H$ and HC*NN*. The pincer *CNN cis*-[RuCl(*CNN*)$(CO)_2$] (**4**) was isolated from **1** by reaction with $NEt_3$. The monocarbonyl complexes *trans*-[$RuCl_2$(HC*NN*)$(PPh_3)(CO)$] (**5**−**7**) were synthesized from [$RuCl_2$(dmf)$(PPh_3)_2(CO)$] and HC*NN* ligands, while the diacetate *trans*-[Ru$(OAc)_2$(HC*NN*)$(PPh_3)(CO)$] (**8**) was obtained from [$Ru(OAc)_2(PPh_3)_2(CO)$]. Carbonylation of *cis*-[RuCl(*CNN*)$(PPh_3)_2$] with CO afforded the pincer derivatives [RuCl(*CNN*)$(PPh_3)(CO)$] (**9**−**11**). Treatment of **9** with Na[$BAr^f$]$_4$ and $PPh_3$ gave the cationic complex *trans*-[Ru(*CNN*)$(PPh_3)_2(CO)$][$BAr^f_4$] (**12**). The dicarbonyl derivatives **1**−**4**, in the presence of $PPh_3$ or $PCy_3$, and the monocarbonyl complexes **5**−**12** catalyzed the transfer hydrogenation (TH) of acetophenone (**a**) in 2-propanol at reflux (S/C = 1000−100000 and TOF up to 100000 $h^{-1}$). Compounds **1**−**3**, with $PCy_3$, and **6** and **8**−**10** were proven to catalyze the TH of carbonyl compounds, including $\alpha,\beta$-unsaturated aldehydes and bulky ketones (S/C and TOF up to 10000 and 100000 $h^{-1}$, respectively). The derivatives **1**−**3** with $PCy_3$ and **5** and **6** catalyzed the hydrogenation (HY) of **a** ($H_2$, 30 bar) at 70 °C (S/C = 2000−10000). Complex **5** was active in the HY of diaryl ketones and aryl methyl ketones, leading to complete conversion at S/C = 10000.




## INTRODUCTION

The search for more efficient transition-metal catalysts for the synthesis of valuable organic compounds is an issue of current relevance for both academia and industry. Among the different metals, ruthenium has been deeply investigated because of its high performance in several organic reactions.[1] In the last few decades great concern has been focused in academia on the improvement of the catalyst (stereo)selectivity for achieving clean organic transformations. Conversely, on account of stringent regulations, industrial attention has been concentrated on atom economy and productivity of the catalysts, which have to be employed at low loading and should display moderate sensitivity against air and substrate impurities. Therefore, robustness and deactivation of the ruthenium species have to be carefully taken into account for the design of a practical catalyst.[2] The catalytic hydrogenation (HY)[3] and transfer hydrogenation (TH)[4] of carbonyl compounds are environmentally friendly and widely accepted methods in industry for the production of a number of organic compounds.[5] A crucial breakthrough for the HY and TH reactions has been the introduction of ligands with an NH functionality, which led to highly active catalysts, entailing an outer-sphere mechanism.[6] The employment of the ampy ligand,[7] by us and other groups, has afforded the catalysts *cis*-[$RuCl_2$(ampy)(PP)] (PP = diphosphine), which allow the reduction of a number of carbonyl compounds with high rate and enantioselectivity.[8] Furthermore, the use of 6-aryl-functionalized ampy ligands has led to cyclometalated pincer[9] *CNN* complexes [RuCl(*CNN*)(PP)] (HC*NN* = Hamtp),[7,10] which display superlative features for the TH and HY of carbonyl compounds with TOF and TON values up to $10^6$ $h^{-1}$ and $10^5$, respectively (Figure 1).

**Received:** December 17, 2018

Downloaded via WEBSTER UNIV on February 21, 2019 at 14:44:18 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.


© XXXX American Chemical Society

DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

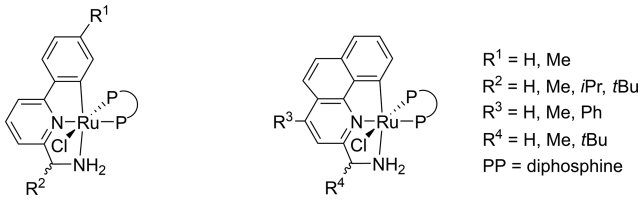



**Figure 1.** 6-Aryl-functionalized ampy and benzo[*h*]quinoline *CNN* ruthenium complexes.

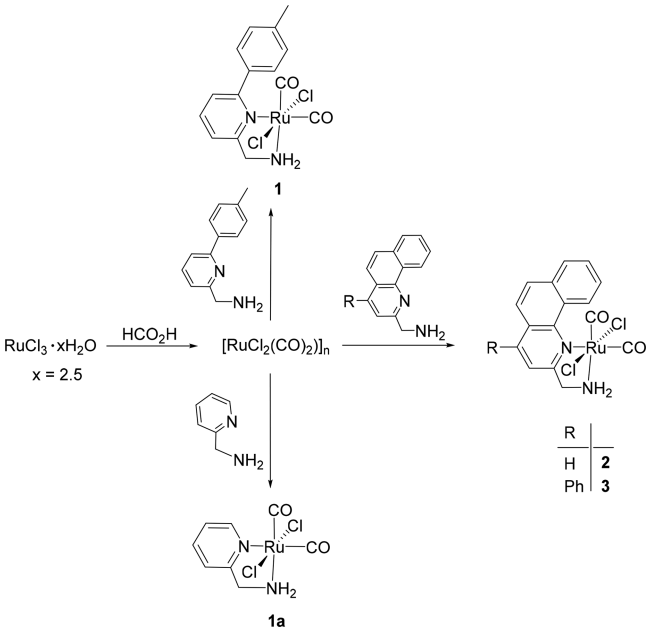
These pincer *CNN* complexes has also been found to be active in other organic transformations, including dehydrogenation,[11] racemization, and deuteration of alcohols[12] and imine hydrogenation.[13] Recently, we have demonstrated that benzo[*h*]quinoline pincer complexes [RuCl(*CNN*)(PP)] (*CNN* = ambq[7,14]) are efficient catalysts for the HY and TH of ketones[10a,14,15] and aldehydes of commercial grade purity (Figure 1).[16] The reduction of aldehydes requires some consideration, as several side reactions may occur during the catalysis, with depletion of selectivity. Since the catalytically active ruthenium hydride species[6a,17] are generated in basic alcohol media, aldehydes displaying reactive $\alpha$-hydrogen atoms can easily undergo aldol condensation,[18] in addition to Claisen–Tishchenko[19] or Cannizzaro reactions[20] for non-enolizable substrates. Furthermore, aldehydes can also decarbonylate with Ru[21] and Os[22] complexes, affording metal carbonyl derivatives, resulting in deactivation and low catalyst productivity.[23] To avoid decarbonylation, employment of carbonyl Ru catalysts has been investigated.[23c,24] In the past decade, monocarbonyl ruthenium complexes have been successfully applied in a number of organic reactions, such as TH and HY of carbonyl compounds,[25] HY of carboxylic and carbonic acid derivatives,[26] alcohol dehydrogenation,[27] and C–X (X = C, N) forming reactions.[28] Relevant examples of monocarbonyl catalysts are $[Ru(TFA)_2(PPh_3)_2(CO)]$,[29] $[Ru(\mu\text{-}OCOC_2F_4OCO)(diphosphine)(CO)]_2$,[27e] [Ru(OAc)(CCN)(CO)],[30] $Ru(CNO)(PPh_3)_2(CO)]$,[31] $[RuCl_2(NNN)(CO)]$ and $[RuCl(NNN)(HOCH_3)(CO)]Cl$,[32] and those reported by Milstein ([RuH(PNN)(CO)]),[33] Gusev ($[RuCl_2(PNN)(CO)]$),[34] and Saito ([RuHCl(PNN)(CO)]).[35] Moreover, we have described that the derivatives $[RuCl((2\text{-}CH_2\text{-}6\text{-}MeC_6H_3)PPh_2)(NN)(CO)]$[36] and $[RuH(Ph_2P(CH_2)_3PPh_2)(NN)(CO)]Cl$[37] (NN = en, ampy[7]) are active in ketone TH reactions. Dicarbonyl ruthenium complexes have been proven to catalyze HY, TH, and dehydrogenation (DHY) reactions involving carbonyl compounds and alcohols, including dynamic kinetic resolution.[38] Examples are $[(\eta^5\text{-}C_5H_4O)_2HRu_2H(CO)_4]$,[38b,39] $[(\eta^5\text{-}C_5R_5)RuCl(CO)_2]$,[40] $[RuCl(PCP)(CO)_2]$,[41] $[RuCl_2(LL')(CO)_2]$ (LL′ = PC, PP, PS),[42] $[RuBr(^RCCC^R)(CO)_2]^{0/+}$ ($^RCCC^R$ = 2,6-bis(1-alkylimidazolylidene)benzene),[43] and $[Ru(CP)(NN)(CO)_2]Cl$.[44] In addition, $[RuCl_2(bpy)(CO)_2]$ and $[Ru(bpy)_2(CO)_2][PF_6]_2$ have been found to promote $CO_2$ reduction[45] and the water-gas shift reaction.[7,46] It is also worth pointing out that these ruthenium mono- and dicarbonyl catalysts have usually been employed at a relatively low S/C ($\leq 10^3$), thus limiting their application.

We report herein a straightforward synthesis of bidentate H*CNN* and pincer *CNN* ruthenium complexes, with one and two CO ligands, which display high catalytic activity and productivity in the reduction of a number of aldehydes and (bulky) ketones.[47] While the monocarbonyl derivatives $[Ru(X)_2(HCNN)(PPh_3)(CO)]$ (X = Cl, OAc) and [RuCl(*CNN*)$(PPh_3)(CO)$] were found to be active in TH and HY reactions, the dicarbonyl derivatives $[RuCl_2(HCNN)(CO)_2]$ and $[RuCl(CNN)(CO)_2]$ required the addition of a phosphine, allowing the reduction at S/C values up to 100000 and TOF values up to 100000 $h^{-1}$.

## RESULTS AND DISCUSSION

**Synthesis of Dicarbonyl Ruthenium Complexes.** Treatment of $RuCl_3 \cdot xH_2O$ with formic acid in a sealed tube at 110 °C for 2 h gave $[RuCl_2(CO)_2]_n$, which reacted cleanly with the Hamtp ligand[7] in ethanol at 80 °C overnight, affording the bidentate H*CNN* complex *trans,cis*-$[RuCl_2(Hamtp)(CO)_2]$ (**1**) isolated in 75% yield, in a one-pot reaction (Scheme 1).

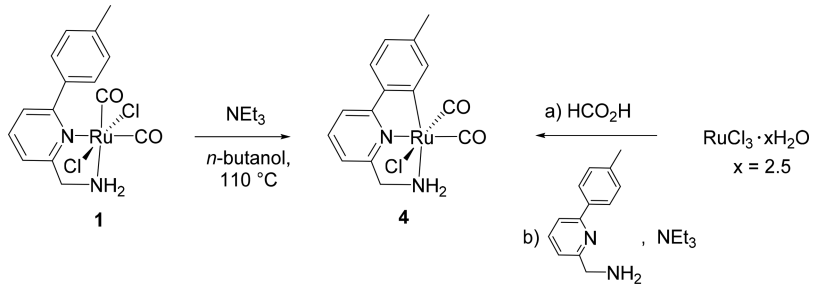
**Scheme 1. Synthesis of H*CNN* Dicarbonyl Complexes *trans,cis*-$[RuCl_2(HCNN)(CO)_2]$ (1–3) and *trans,cis*-$[RuCl_2(ampy)(CO)_2]$ (1a)**



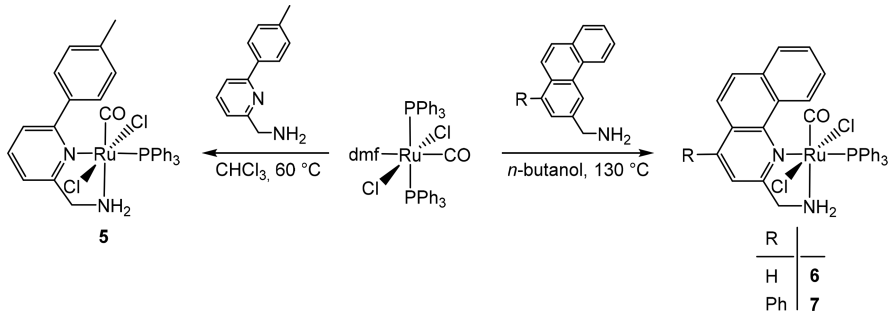

Complex **1** in $CDCl_3$ shows two triplets in the $^1H$ NMR spectrum at $\delta$ 4.78 and 4.19 for methylene and amino groups of the H*CNN* ligand. The $^{13}C\{^1H\}$ NMR spectrum displays two singlets at $\delta$ 195.5 and 190.3 for the CO groups and a signal at $\delta$ 51.2 for the $CH_2N$ group, slightly shifted downfield in comparison to the free ligand ($\delta$ 48.2),[10e,48] suggesting a configuration of **1** with two cis carbonyls and two trans chlorine atoms. The strong IR $\nu_{CO}$ adsorption bands at 2067 and 1998 $cm^{-1}$ can be attributed to the two cis CO groups. These data are similar to those observed for the related *trans,cis*-$[RuCl_2(ampy)(CO)_2]$ (**1a**), which is prepared from $[RuCl_2(CO)_2]_n$ and ampy[7] in an ethanol/water (3/1 in volume) mixture at reflux and isolated in 78% yield (Scheme 1). The triplets at $\delta$ 4.73 and 4.22 are for the $CH_2N$ and $NH_2$ moieties, whereas the $^{13}C\{^1H\}$ NMR resonances of the two CO groups appear at $\delta$ 195.9 and 192.7. In the IR spectrum the two cis CO groups lead to two $\nu_{CO}$ adsorptions at 2054 and 1991 $cm^{-1}$, close to those of the *trans,cis*-$[RuCl_2(bpy)(CO)_2]$ derivative.[49] Similarly to **1**, complexes $[RuCl_2(Hambq)(CO)_2]$ (**2**) and $[RuCl_2(Hambq^{Ph})(CO)_2]$ (**3**), containing the more rigid benzo[*h*]quinoline H*CNN*


DOI: 10.1021/acs.organomet.8b00919
Organometallics XXXX, XXX, XXX–XXX

**Scheme 2. Syntheses of the Cyclometalated Dicarbonyl Complex *cis*-[RuCl(amtp)(CO)$_2$] (4)**




**Scheme 3. Synthesis of the HCNN Monocarbonyl Complexes *trans*-[RuCl$_2$(HCNN)(PPh$_3$)(CO)] (5–7)**




ligands,[50] were obtained by reaction of [RuCl$_2$(CO)$_2$]$_n$ with Hambq and Hambq$^{Ph\ 7}$ in ethanol at reflux and isolated in 49 and 72% yields, respectively (Scheme 1). The $^1$H NMR spectrum of **2** in $CD_2Cl_2$ shows two broad resonances at $\delta$ 4.59 and 3.69 for the $CH_2$ and the $NH_2$ groups, whereas a doublet of doublets at $\delta$ 9.07 is ascribed to the H-10 proton of the benzo[*h*]quinoline moiety, indicating that the ligand is not cyclometalated. The CO groups of **2** appear as singlets at $\delta$ 200.0 and 190.4 in the $^{13}C\{^1H\}$ NMR spectrum, while the $CH_2N$ carbon is at $\delta$ 52.3. The IR spectrum reveals two stretching bands at 2059 and 1985 cm$^{-1}$ for the cis CO moieties. Likewise, **3** displays a resonance at $\delta$ 9.42 in the $^1$H NMR spectrum for the aromatic H-10 proton, whereas the two $^{13}C\{^1H\}$ NMR singlets at $\delta$ 201.2 and 194.4 are ascribed to the CO ligands.

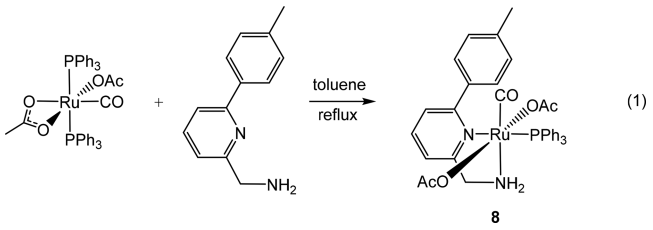
Treatment of **1** with an excess of triethylamine (10 equiv) in *n*-butanol at 110 °C overnight afforded the cyclometalated pincer *CNN* derivative *cis*-[RuCl(amtp)(CO)$_2$] (**4**) in 58% yield (Method A for compound **4** in the Experimental Section) (Scheme 2). Alternatively, compound **4** was also obtained directly through a one-pot synthesis from RuCl$_3$·*x*H$_2$O/HCO$_2$H (Method B for compound **4**), followed by reaction with Hamtp and triethylamine in *n*-butanol (Scheme 2). In the $^1$H NMR spectrum of **4** the diastereotopic methylene protons of the *CNN* ligand appear as a doublet of doublets at $\delta$ 4.65 and a multiplet at $\delta$ 4.41, whereas the amino group give two broad signals at $\delta$ 4.06 and 3.46. The $^{13}C\{^1H\}$ NMR spectrum displays the CO signals at $\delta$ 200.4 and 194.0, while the resonances at $\delta$ 164.2 and 52.3 are for the ortho-metalated carbon and the $CH_2N$ moiety, respectively. The cis CO ligands show two strong stretching bands in the IR spectrum at 2028 and 1958 cm$^{-1}$. A comparison of the cyclometalation reaction of Hamtp with [RuCl$_2$(PPh$_3$)$_3$][50] and [RuCl$_2$(PPh$_3$)(dppb)],[10e] with respect to [RuCl$_2$(CO)$_2$]$_n$, indicates that the C–H activation occurs more easily with ruthenium phosphine precursors.

**Synthesis of Monocarbonyl Ruthenium Complexes.** The monocarbonyl ruthenium complex *trans*-[RuCl$_2$(Hamtp)(PPh$_3$)(CO)] (**5**) was synthesized in 68% yield by reaction of the precursor [RuCl$_2$(dmf)(PPh$_3$)$_2$(CO)] with Hamtp in chloroform at 60 °C overnight (Scheme 3).

The $^1$H NMR spectrum of **5** displays two triplets at $\delta$ 4.50 and 3.13 for the $CH_2$ and the amino groups, whereas the $^{31}P\{^1H\}$ NMR resonance is at $\delta$ 54.5. These NMR data are similar to those of *trans*-[RuCl$_2$(ampy)(PPh$_3$)(CO)],[25a] displaying the CO trans to the $NH_2$ moiety. For **5**, the $^{13}C\{^1H\}$ NMR doublet at $\delta$ 200.5 ($^2J$(C,P) = 21.5 Hz) is for CO cis to the $PPh_3$ group, whereas the doublet at $\delta$ 50.1 is for the $CH_2N$ moiety. The CO ligand exhibits a stretching band at 1947 cm$^{-1}$ in the IR spectrum, close to that of *trans*-[RuCl$_2$(ampy)(PPh$_3$)(CO)].[25a] Likewise, *trans*-[RuCl$_2$(Hambq)(PPh$_3$)(CO)] (**6**) and *trans*-[RuCl$_2$(Hambq$^{Ph}$)(PPh$_3$)(CO)] (**7**) were obtained by the reaction of [RuCl$_2$(dmf)(PPh$_3$)$_2$(CO)] with Hambq and HCl·Hambq$^{Ph}$ [51] with NBu$_3$ in *n*-butanol at reflux overnight, leading to the products in 93% and 44% yields, respectively (Scheme 3). The syntheses of **6** and **7** required higher temperature with respect to that for **5**, possibly due to the higher rigidity of the benzo[*h*]quinoline ligands, in comparison to Hamtp, hindering the coordination of the heterocyclic moiety. Complexes **6** and **7** show NMR and IR data similar to those observed for **5**, with $^{31}P\{^1H\}$ NMR resonances at $\delta$ 53.4 and 53.5, whereas the $^{13}C\{^1H\}$ NMR carbonyl signals appear as doublets at $\delta$ 200.4 and 200.5, respectively. The aromatic H-10 protons for **6** and **7** are at $\delta$ 9.29 and 9.08, indicating no cyclometalation. Finally, the IR spectra of **6** and **7** display a $\nu_{CO}$ band at 1920 and 1924 cm$^{-1}$, respectively. The reaction between the acetate precursor [Ru(OAc)$_2$(PPh$_3$)$_2$(CO)] and the ligand Hamtp in toluene at reflux for 48 h afforded the *trans*-[Ru(OAc)$_2$(Hamtp)(PPh$_3$)(CO)] (**8**) in 40% yield (eq 1).

The $^1$H NMR spectrum of **8** in $CD_2Cl_2$ shows a doublet of doublets at $\delta$ 4.41 and a multiplet at $\delta$ 4.21 for the two diastereotopic methylene protons. The $NH_2$ group gives two


DOI: 10.1021/acs.organomet.8b00919
Organometallics XXXX, XXX, XXX–XXX

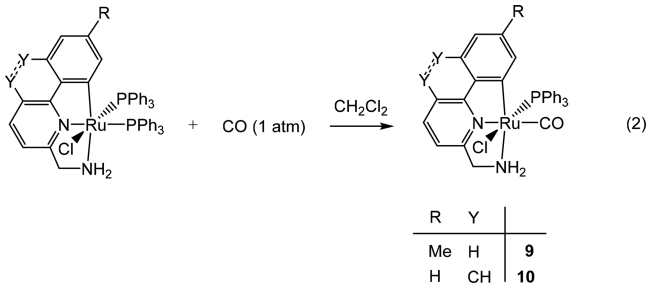



(1)

8

signals at $\delta$ 8.16 and 1.57; the low-field resonance is consistent with an intramolecular N−H···O hydrogen bond interaction with one acetate. The methyl signals of the acetate ligands are at $\delta$ 2.07 and 1.20. In the $^{13}C\{^1H\}$ NMR spectrum the CO appears as a doublet at $\delta$ 202.9 ($^2J$(C,P) = 17.4 Hz), whereas the acetate carbonyl shifts are at $\delta$ 180.5 and 177.7. The $^{31}P\{^1H\}$ NMR resonance of the $PPh_3$ is at $\delta$ 54.4, very close to the value observed for **5** ($\delta$ 54.5), while the IR $\nu_{CO}$ adsorption band of the CO is at 1914 $cm^{-1}$. Finally the infrared stretching bands at 1597 and 1572 $cm^{-1}$ are characteristic of $\nu_{OCO}$ of two monodentate acetate ligands, the second slightly red shifted due to the presence of a hydrogen bond with the amino group.[52] Therefore, the spectroscopic data for **8** are consistent with the arrangement observed for **5**, with one acetate ligand interacting with the $NH_2$ moiety.

The pincer *CNN* monocarbonyl complex [RuCl(amtp)-$(PPh_3)$(CO)] (**9**) was easily prepared by treatment of *cis*-[RuCl(amtp)$(PPh_3)_2$] with CO (1 atm) in $CH_2Cl_2$ at room temperature overnight by $PPh_3$ substitution and was isolated in 59% yield (eq 2).




(2)

| R | Y | |
|---|---|---|
| Me | H | **9** |
| H | CH | **10** |

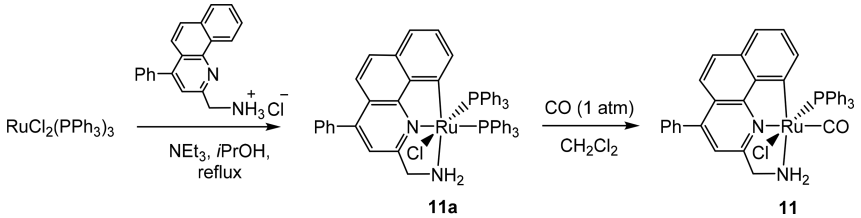
The $^{31}P\{^1H\}$ NMR spectrum of **9** in $CD_2Cl_2$ shows a singlet at $\delta$ 57.6, consistent with the $PPh_3$ trans to chlorine,[53] whereas the CO ligand is trans to the pyridyl nitrogen. In the $^1H$ NMR spectrum the diastereotopic methylene protons appear as two doublets of doublets at $\delta$ 4.25 and 3.41, while the amino group is at $\delta$ 3.86 and 2.79. The $^{13}C\{^1H\}$ NMR doublet at $\delta$ 176.3 ($^2J$(C,P) = 12.3 Hz) is for the cyclometalated carbon, whereas the doublet at $\delta$ 207.5 ($^2J$(C,P) = 18.2 Hz) is for the CO moiety. For **9**, the IR stretching band of CO is at 1905 $cm^{-1}$. Attempts to isolate **9** by cyclometalation of **5** in 2-propanol or *n*-butanol at reflux and in the presence of a base ($NEt_3$ or $NBu_3$) failed, affording a mixture of **9** and uncharacterized products.

Similarly to **9**, the benzo[*h*]quinoline *CNN* derivative [RuCl(ambq)$(PPh_3)$(CO)] (**10**) was prepared by treatment of the pincer precursor *cis*-[RuCl(ambq)$(PPh_3)_2$] with CO at room temperature and isolated in 80% yield. The $^1H$ NMR spectrum of **10** resembles that of **9**, with two signals at $\delta$ 4.51 and 3.70 for the diastereotopic $CH_2N$ protons, whereas the $NH_2$ resonances are at $\delta$ 4.03 and 2.86. The doublet at $\delta$ 8.02 is attributed to the CH proton close to the ortho-metalated carbon atom. The $^{13}C\{^1H\}$ NMR signal of the CO ligand is a doublet at $\delta$ 207.8 ($^2J$(C,P) = 17.5 Hz), whereas the cyclometalated carbon atom gives a doublet at $\delta$ 172.1 ($^2J$(C,P) = 12.8 Hz). The $^{31}P\{^1H\}$ NMR spectrum of **10** shows a singlet at $\delta$ 58.5, while the IR $\nu_{CO}$ adsorption band is at 1922 $cm^{-1}$. The complex [RuCl($ambq^{Ph}$)$(PPh_3)$(CO)] (**11**) was obtained from the pincer precursor *cis*-[RuCl($ambq^{Ph}$)-$(PPh_3)_2$] (**11a**), which was prepared following the procedure described for the synthesis of **10**. Thus, **11a** was isolated in 88% yield by reaction of $[RuCl_2(PPh_3)_3]$ with HCl·$Hambq^{Ph}$ [51] and 10 equiv of $NEt_3$ in 2-propanol at reflux (Scheme 4).

The $^{31}P\{^1H\}$ NMR spectrum of **11a** in $CDCl_3$ shows two doublets at $\delta$ 57.3 and 50.8 with a $^2J$(P,P) value of 33.7 Hz. In the $^1H$ NMR spectrum, the signals for the diastereotopic $CH_2N$ protons are at $\delta$ 4.31 and 3.61, whereas the $NH_2$ resonances are at $\delta$ 4.02 and 3.02. The $^{13}C\{^1H\}$ NMR spectrum of **11a** exhibits a doublet at $\delta$ 177.9 ($^2J$(C,P) = 3.9 Hz) for the cyclometalated carbon atom. Reaction of **11a** with CO (1 atm) in $CH_2Cl_2$ at room temperature afforded **11**, isolated in 83% yield, displaying much the same spectroscopic data as the related derivative **10** (Scheme 4). The molecular structure of **11** was confirmed by an X-ray single-crystal diffraction measurement carried out at 123 K. An ORTEP style drawing of **11** is displayed in Figure 2.

The ruthenium center of **11** is in a pseudo-octahedral environment with the cyclometalated *CNN* ligand bound to the metal in a terdentate fashion, forming two five-membered chelate rings. The Ru−N2 bond distance of the benzo[*h*]-quinoline trans to the CO is significantly shorter (2.0719(17) Å) than the Ru−N1 amino bond distance (2.2737(18) Å), in agreement with the geometrical constraints of the terdentate ligand showing narrow N2−Ru−C2 and N1−Ru−N2 bond angles (80.78(7) and 74.45(6)°, respectively) and the higher trans influence exerted by the aryl group. The amino nitrogen N1 and the $CHNH_2$ carbon are displaced by −0.182 and +0.175 Å, respectively, from the best-fit plane through the aromatic part of the *CNN* moiety. This arrangement is characterized by one N−H and the Ru−Cl1 bonds that are almost parallel (H−N1−Ru−Cl1 dihedral angle of about −12.26°, with an H···Cl1 distance of 2.69 Å), suggesting a possible intramolecular hydrogen bond interaction.[54]

**Scheme 4. Synthesis of *cis*-[RuCl($ambq^{Ph}$)$(PPh_3)_2$] (11a) and [RuCl($ambq^{Ph}$)$(PPh_3)$(CO)] (11)**




11a 11



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

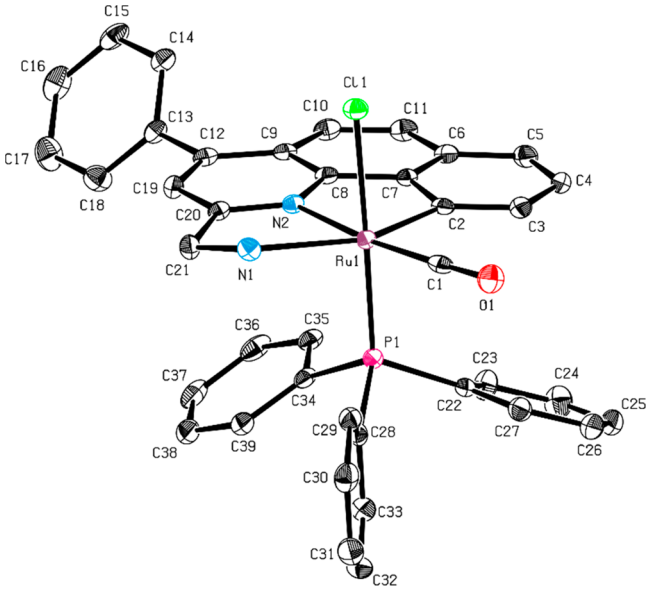
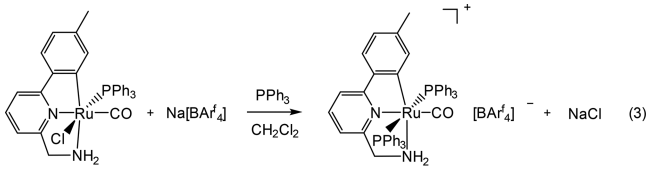



**Figure 2.** ORTEP style plot of compound **11** in the solid state (CCDC 1868440). Ellipsoids are drawn at the 50% probability level. H atoms are omitted for clarity. Selected bond lengths (Å) and angles (deg): Ru1−C1 1.847(2), Ru1−C2 2.042(2), Ru1−N2 2.0719(17), Ru1−N1 2.2737(18), Ru1−P1 2.2763(5), Ru1−Cl1 2.4846(5); C1−Ru1−C2 92.25(9), C1−Ru1−N2 172.74(8), C2−Ru1−N2 80.78(7), C1−Ru1−N1 112.30(8), C2−Ru1−N1 154.78(7), N2−Ru1−N1 74.45(6), C1−Ru1−P1 88.70(6), C2−Ru1−P1 89.01(6), N2−Ru1−P1 93.18(5), N1−Ru1−P1 96.94(5), C1−Ru1−Cl1 92.58(6), C2−Ru1−Cl1 91.39(6), N2−Ru1−Cl1 85.61(5), N1−Ru1−Cl1 82.16(5), P1−Ru1−Cl1 178.643(19).

The cationic diphosphine complex *trans*-[Ru(amtp)-$(PPh_3)_2(CO)][BAr^f_4]$ (**12**), isolated in 79% yield, was promptly obtained by treatment of **9** with $Na[BAr^f_4]$ ($Ar^f$ = 3,5-$(CF_3)_2C_6H_3$) and $PPh_3$ in $CH_2Cl_2$ at room temperature, by the replacement of chlorine with $PPh_3$ (eq 3).




The $^{31}P\{^1H\}$ NMR spectrum of **12** in $CD_2Cl_2$ shows a singlet at $\delta$ 35.5, while the $^1H$ NMR signals at $\delta$ 3.53 and at $\delta$ 2.95 belong to the methylene and the amino groups, respectively. The $^{13}C\{^1H\}$ NMR resonances of the CO and the cyclometalated carbon atoms appear as triplets at $\delta$ 205.9 ($^2J$(C,P) = 15.7 Hz) and 169.4 ($^2J$(C,P) = 10.5 Hz), respectively, indicating a trans arrangement of $PPh_3$ ligands. Finally, **12** shows a strong IR $\nu_{CO}$ adsorption band at 1914 $cm^{-1}$. Thus, the NMR and IR data of the coordinated CO of **12** and **9** are much the same ($\Delta\delta$ = 1.6 and $\Delta\nu_{CO}$ = 9 $cm^{-1}$), consistent with the presence of a trans pyridine nitrogen. It is likely that the chlorine abstraction from **9** with $Na[BAr^f_4]$ may led to a cationic species of the type $[Ru(amtp)(PPh_3)(CO)(solvent)_n][BAr^f_4]$ ($n$ = 0, 1), which rapidly reacted with the $PPh_3$ to cleanly afford complex **12**, also in accordance with the isolated solvato complex [Ru(amtp)(dppb)(2-propanol)]-$[BAr^f_4]$.[55]

**Reduction of Aldehydes and Ketones via TH and HY Catalyzed by Carbonyl HCNN Ruthenium Complexes.** The catalytic activity of the complexes **1**−**12** was investigated in the reduction of the model substrate acetophenone **a** via TH and HY, in the presence of alkoxides. Complexes **1**−**4**, with phosphines, and the derivatives **5**−**11** efficiently catalyzed the selective TH of different (bulky) ketones and (unsaturated) aldehydes, in short times at S/C = 1000−100000 (Scheme 5).

The dicarbonyl HCNN complexes **1**−**4** (S/C = 1000) did not show appreciable activity in the TH of **a** (0.1 M) in 2-propanol at reflux in the presence of NaO*i*Pr (2 mol %) with less than of 2% of conversion in 2 h (Table S1 in the Supporting Information). Addition of a phosphine, namely $PPh_3$ or $PCy_3$ (2 equiv) in situ, drastically increased their activity. Complex **1** in the presence of $PPh_3$ afforded quantitative reduction of **a** in 1 h with an S/C ratio of 1000 (TOF = 1000 $h^{-1}$), whereas with $PCy_3$ the TH occurred in less than 1 min (Table 1, entries 1 and 2).

By employment of $PCy_3$ at S/C = 10000, the reaction was complete in 20 min (TOF = 100000 $h^{-1}$), whereas at S/C = 50000−100000, quantitative reduction of **a** was achieved within 4 h (Table 1, entries 3 and 4, and Table S1 in the Supporting Information).

It is worth pointing out that the related complex *trans,cis*-$[RuCl_2(ampy)(CO)_2]$ (**1a**) was not active, and in the presence of $PCy_3$ the TH of **a** occurred in 2 h at a low rate (TOF = 800 $h^{-1}$; Table 1, entry 5), indicating that the phenyl substituent in the 6-position of the HCNN ligand is crucial to achieve high catalytic activity.

The benzo[*h*]quinoline derivatives **2** and **3** displayed a similar behavior with S/C = 1000, affording 97% of reduction of **a** in 1 h with $PPh_3$, whereas in the presence of $PCy_3$, **2** and **3** led to complete conversion in 15 and 30 min, respectively (Table 1, entries 6−9). The cyclometalated pincer ruthenium dicarbonyl derivative **4** in the presence of $PCy_3$ afforded 97% reduction of **a** in 20 min at S/C = 1000 (TOF = 4300 $h^{-1}$), indicating a lower activity with respect to **1** (entry 11). The monocarbonyl HCNN derivative **5** displayed good performance (TOF = 12000 $h^{-1}$), allowing quantitative reduction of **a** in 20 min at S/C = 1000 (entry 12). An increase in the rate was observed by addition of the strongly basic $PCy_3$ to **5** (TOF = 18700 $h^{-1}$; entry 15). Complex **5** efficiently catalyzed the TH of **a** also in the range of S/C 5000−50000, leading quantitatively to 1-phenylethanol in 40 min (S/C = 10000, TOF = 8000 $h^{-1}$) and 42 h (S/C = 50000), proving that **5** was a productive catalyst (entries 13 and 14 and Table S1 in the Supporting Information). The benzo[*h*]quinoline complexes **6** and **7** led to 99% conversion of **a** at S/C 1000 in 10 and 20 min, respectively, with a rate comparable to that observed for **5** (TOF = 11000−12000 $h^{-1}$). These catalysts were also active at a lower loading (S/C 10000), with complete reduction of **a** in 2 h and 45 min for **6** and **7** (TOF up to 20000 $h^{-1}$; entries 16−19). The diacetate ruthenium derivative **8** gave 99% conversion of **a** in 10 min and 1 h, at S/C = 1000 and 10000, respectively (TOF = 20000 and 17000 $h^{-1}$; entries 20 and 21). The higher rate of **8** in comparison to that of **5** can be attributed to the easier substitution of the acetate with the isopropoxide, with respect to the chloride. A similar behavior was observed for the [RuX(*CNN*)(dppb)] complexes (X = Cl, OAc) which catalyze the TH of **a** with TOF values of 1100000 and 1800000 $h^{-1}$ for the chloride and acetate derivative, respectively.[10e,53] Finally, the pincer *CNN* monocarbonyl complexes **9**−**11** proven to be highly active catalysts for the


DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

**Scheme 5. TH of Ketones and Aldehydes Catalyzed by Ruthenium Carbonyl Complexes 1−12**

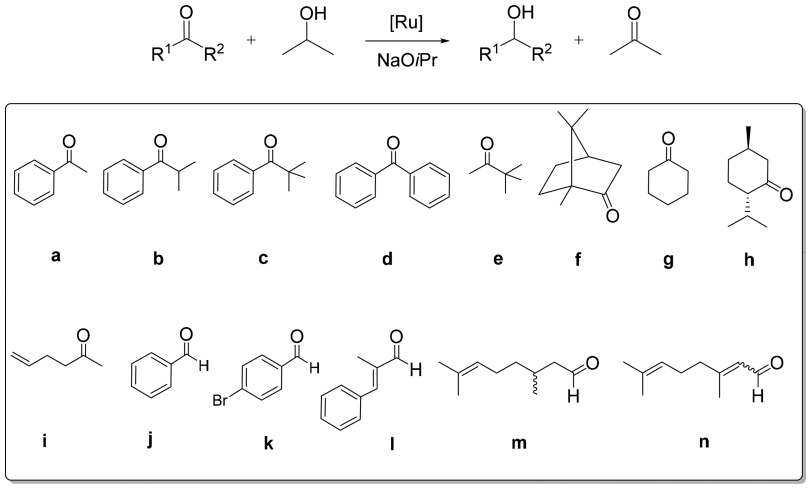



**Table 1. Catalytic TH of Acetophenone (0.1 M) with Complexes 1−12 in 2-Propanol at 82 °C in the Presence of 2 mol % NaO*i*Pr**

| entry | complex | S/C | ligand (2 equiv) | time (min) | conversn[a] (%) | TOF[b] ($h^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | **1** | 1000 | $PPh_3$ | 60 | 99 | 1000 |
| 2 | **1** | 1000 | $PCy_3$ | 1 | 99 | >30000 |
| 3 | **1** | 10000 | $PCy_3$ | 20 | 99 | 100000 |
| 4 | **1** | 100000 | $PCy_3$ | 240 | 99 | 95000 |
| 5 | **1a** | 1000 | $PCy_3$ | 120 | 99 | 800 |
| 6 | **2** | 1000 | $PPh_3$ | 60 | 97 | |
| 7 | **2** | 1000 | $PCy_3$ | 15 | 96 | |
| 8 | **3** | 1000 | $PPh_3$ | 60 | 97 | |
| 9 | **3** | 1000 | $PCy_3$ | 30 | 99 | |
| 10 | **4** | 1000 | $PPh_3$ | 60 | 99 | |
| 11 | **4** | 1000 | $PCy_3$ | 20 | 97 | 4300 |
| 12 | **5** | 1000 | | 20 | 99 | 12000 |
| 13 | **5** | 10000 | | 40 | 99 | 8000 |
| 14 | **5** | 25000 | | 1 day | 99 | 2200 |
| 15 | **5** | 1000 | $PCy_3$ | 20 | 97 | 18700 |
| 16 | **6** | 1000 | | 10 | 99 | 11600 |
| 17 | **6** | 10000 | | 120 | 99 | 10500 |
| 18 | **7** | 1000 | | 20 | 99 | 12000 |
| 19 | **7** | 10000 | | 45 | 99 | 20000 |
| 20 | **8** | 1000 | | 10 | 99 | 20000 |
| 21 | **8** | 10000 | | 60 | 98 | 17000 |
| 22 | **9** | 10000 | | 20 | 99 | 86000 |
| 23 | **9** | 50000 | | 240 | 99 | 55000 |
| 24 | **10** | 1000 | | 15 | 96 | |
| 25 | **10**[c] | 1000 | | 30 | 95 | |
| 26 | **11** | 10000 | | 60 | 99 | 18000 |
| 27 | **12** | 1000 | | 10 | 99 | 45000 |
| 28 | **12** | 10000 | | 240 | 98 | 16000 |
| 29 | $[RuCl_2(PCy_3)_2(CO)_2]$ | 1000 | | 960 | 90 | 120 |
| 30 | $[RuCl_2(PCy_3)_2(CO)_2]$ | 1000 | ampy | 480 | 91 | 480 |
| 31 | $[RuCl_2(PCy_3)_2(CO)_2]$ | 1000 | Hamtp | 10 | 99 | 49000 |

[a]The conversions were determined by GC analysis. [b]Turnover frequency (moles of ketone converted to alcohol per mole of catalyst per hour) at 50% conversion. [c]Reaction was performed using 5 mol % $K_2CO_3$ as base.

TH of **a**. $[RuCl(amtp)(PPh_3)(CO)]$ (**9**) afforded extremely fast and quantitative reduction of **a** in 20 min at S/C = 10000 (TOF = 86000 $h^{-1}$), whereas at S/C = 50000, complete conversion was achieved in 4 h (TOF = 55000 $h^{-1}$; entries 22 and 23). The benzo[*h*]quinoline ruthenium complexes **10** and **11** exhibited a lower activity, affording the reduction of **a** in 15 min for **10** (S/C = 1000) and in 1 h for **11** (S/C = 10000, TOF = 18000 $h^{-1}$; entries 24 and 26). Use of $K_2CO_3$ in place of NaO*i*Pr with **10** afforded quantitative reduction of **a** in longer reaction times, this protocol being relevant for base-sensitive substrates, such as aldehydes (entry 25).[16b] The cationic complex **12** allowed reduction of **a** in 10 min at S/C =



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

**Table 2. TH of Ketones and Aldehydes (0.1 M) with Complexes 1−3, 6, and 8−10 in 2-Propanol at 82 °C in the Presence of 2 mol % NaO*i*Pr**

| entry | complex | ligand (2 equiv) | substrate | S/C | time (min) | conversn[a] (%) | TOF[b] ($h^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | **1** | $PCy_3$ | **b** | 10000 | 15 | 99 | 95000 |
| 2 | **1** | $PCy_3$ | **c** | 10000 | 20 | 99 | 75000 |
| 3 | **1** | $PCy_3$ | **d** | 10000 | 15 | 96 | 100000 |
| 4 | **1** | $PCy_3$ | **e** | 10000 | 20 | 98 | 75000 |
| 5 | **1** | $PCy_3$ | **f** | 2000 | 60 | 97 | 5000 |
| 6 | **1** | $PCy_3$ | **g** | 10000 | 60 | 97 | 20000 |
| 7 | **1** | $PCy_3$ | **i** | 10000 | 30 | 98 | 60000 |
| 8 | **2** | $PPh_3$ | **j** | 1000 | 60 | 98 | 1700 |
| 9 | **2** | $PCy_3$ | **j** | 1000 | 2 | 99 | 12000 |
| 10 | **3** | $PPh_3$ | **j** | 1000 | 60 | 99 | 1000 |
| 11 | **3** | $PCy_3$ | **j** | 1000 | 1 | 99 | >30000 |
| 12 | **6**[c] | | **h** | 10000 | 8 h | 99[d] | 5600 |
| 13 | **6**[c] | | **m** | 1000 | 10 | 99 | 6000 |
| 14 | **6**[c] | | **m** | 10000 | 8 h | 99 | 3300 |
| 15 | **6**[c] | | **n**[e] | 1000 | 30 | 99[f] | |
| 16 | **8**[c] | | **h** | 1000 | 30 | 99[g] | 8000 |
| 17 | **8**[c] | | **h** | 10000 | 56 h | 81[g] | 900 |
| 18 | **8**[c] | | **n**[e] | 1000 | 10 | 99[f] | |
| 19 | **8**[c] | | **n**[e] | 10000 | 90 | 98[f] | |
| 20 | **9** | | **k** | 10000 | 10 | 99 | 80000 |
| 21 | **9** | | **k** | 25000 | 30 | 99 | 65000 |
| 22 | **9** | | **d** | 10000 | 40 | 99 | 32000 |
| 23 | **9** | | **d** | 25000 | 90 | 99 | 25000 |
| 24 | **9** | | **l** | 1000 | 40 | 93 | |
| 25 | **10** | | **d** | 1000 | 30 | 94 | |
| 26 | **10** | | **j** | 1000 | 60 | 98 | |

[a]The conversions were determined by GC analysis. [b]Turnover frequency (moles of ketone converted to alcohol per mole of catalyst per hour) at 50% conversion. [c]Reactions were conducted employing 5 mol % $K_2CO_3$ as base. [d](−)-menthol/(+)-neomenthol/(+)-isomenthol/(+)-neoisomenthol = 71/23/4/2. [e]geranial/neral = 2/1. [f]geraniol/nerol = 2/1. [g](−)-menthol/(+)-neomenthol/(+)-isomenthol/(+)-neoisomenthol = 75/18/4/3.

1000 (TOF = 45000 $h^{-1}$) and was also active at lower loading (S/C 10000), affording complete conversion in 4 h (entries 27 and 28), possibly through a displacement of a $PPh_3$ group under these catalytic conditions.

Since an acceleration effect was observed with the H*CNN* complex **1** upon addition of $PCy_3$, we carried out control experiments starting from the well-known *cis*,*trans*,*cis*-$[RuCl_2(PCy_3)_2(CO)_2]$ precursor in the presence of H*CNN*. The in situ generated catalyst, obtained by refluxing a 2-propanol solution of $[RuCl_2(PCy_3)_2(CO)_2]$ with Hamtp (2 h), promoted the quantitative reduction of acetophenone in 10 min (TOF = 49000 $h^{-1}$ at S/C 1000; Table 1, entry 31). Conversely, using the ruthenium dicarbonyl precursor alone or in the presence of ampy led to about 90% conversion of **a** with much lower rates (TOFs = 120 and 480 $h^{-1}$, respectively) and with very long reaction times (16 and 8 h; entries 29 and 30). These results clearly indicated that *cis*,*trans*,*cis*-$[RuCl_2(PCy_3)_2(CO)_2]$ displayed poor activity in the TH reactions under our conditions, in agreement with the literature data for the TH of cyclohexanone and HY of aldehydes occurring at high temperature,[56] and that the use of H*CNN* ligands which allow cyclometalation is crucial to achieve high rate and high productivity in the ketone TH (see below).

The most active catalysts for the TH of **a** were tested in the reduction of (bulky) ketones and aldehydes (Scheme 5). Isobutyrophenone **b** and the bulky pivalophenone **c** were quantitatively reduced to the corresponding alcohols in 15 and 20 min, respectively, with the **1**/$PCy_3$ system at S/C = 10000 with TOF values of up to 95000 $h^{-1}$ (Table 2; entries 1 and 2).

This catalytic system converted benzophenone **d** to benzhydrol in 15 min at S/C = 10000 with TOF = 100000 $h^{-1}$ (Table 2, entry 3). The sterically hindered dialkyl pinacolone **e** and the cyclic (*R*)-camphor **f** were quantitatively converted to pinacolyl alcohol and to an isoborneol/borneol mixture (85/15) in 20 min and 1 h at S/C = 10000 and 2000, respectively (TOF = 75000 and 5000 $h^{-1}$; entries 4 and 5). It is worth noting that bulky ketones were usually reduced at considerably lower S/C on account of the difficulty of the substrate to approach the metal center.[57,58] Complex **1**, in the presence of $PCy_3$, was proved to catalyze the TH of cyclohexanone **g** in 1 h (97% conversion, S/C = 10000) and allylacetone **i** in 30 min (98% conversion) to the corresponding alcohols, with no reduction of the C═C bond (entries 6 and 7). Benzaldehyde **j** was completely and rapidly reduced to benzyl alcohol by the benzo[*h*]quinoline dicarbonyl ruthenium complexes **2** and **3** with $PCy_3$ in a few minutes (S/C = 1000, TOF up to 30000 $h^{-1}$). Employment of $PPh_3$ instead of $PCy_3$ afforded the TH of benzaldehyde **j** but with longer reaction times (60 min; entries 8−11). The benzo[*h*]quinoline derivative **6** quantitatively reduced (−)-menthone **h** at S/C = 10000 in 8 h, with a good stereoselectivity for (−)-menthol (71%; entry 12). (±)-*β*-Citronellol was obtained from (±)-citronellal **m** in 99% yield with **6** in 10 min and 8 h, respectively, at S/C 1000 and 10000 (entries 13 and 14). The commercial citral **n**, consisting of the



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

**Scheme 6. HY of Ketones Catalyzed by Ruthenium Carbonyl Complexes 1−11**

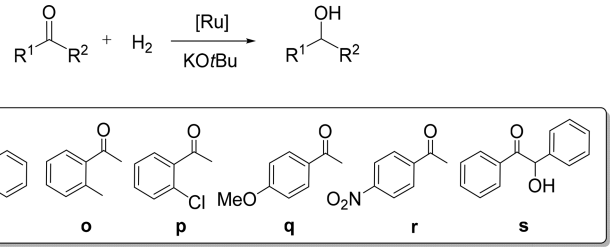



**Table 3. HY of Ketones (2 M) with Complexes 1−3, 5, and 6 under $H_2$ (30 bar) with KO*t*Bu at 70 °C**

| entry | complex | ligand (2 equiv) | substrate | S/C | solvent | KOtBu (mol %) | time (h) | conversn[a] (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | **1** | $PPh_3$ | **a** | 2000 | EtOH | 2 | 16 | 34 |
| 2 | **1** | $PCy_3$ | **a** | 2000 | EtOH | 2 | 16 | 46 |
| 3 | **1** | $PCy_3$ | **a** | 2000 | MeOH | 5 | 16 | 99 |
| 4 | **1**[b] | $PCy_3$ | **a** | 2000 | MeOH | 5 | 16 | 99 |
| 5 | **2** | $PCy_3$ | **a** | 2000 | MeOH | 5 | 16 | 99 |
| 6 | **3** | $PCy_3$ | **a** | 2000 | MeOH | 5 | 16 | 99 |
| 7 | **5** | | **a** | 2000 | MeOH | 5 | 16 | 63 |
| 8 | **6** | | **a** | 2000 | MeOH | 5 | 16 | 99 |
| 9 | **5** | | **d** | 500 | EtOH | 5 | 16 | 99 |
| 10 | **5** | | **o** | 10000 | EtOH | 2 | 16 | 46 |
| 11 | **5** | | **p** | 10000 | EtOH | 5 | 16 | 99 |
| 12 | **5** | | **q** | 500 | EtOH | 5 | 16 | 99 |
| 13 | **5** | | **r** | 10000 | EtOH | 5 | 16 | 99 |
| 14 | **5** | | **s** | 10000 | EtOH | 5 | 16 | 63 |

[a]HY was carried out in an eight-vessel Endeavor Biotage system, and the conversions were determined by GC analysis. [b]Reaction was performed employing 5 mol % KOH as base.

*E* and *Z* geranial and neral isomers in a ratio of about 2:1, was converted to a mixture of the respective alcohols (geraniol and nerol) with **6** in 30 min (99% conversion at S/C = 1000), whereas the diacetate ruthenium complex **8** led to similar results in 10 min (entries 15 and 18). $K_2CO_3$ was used instead of NaO*i*Pr for the TH of **m** and **n** to prevent aldol condensation and C═C hydrogenation side reactions in strong basic media. Compound **8** proved to be active also at lower loading, promoting the complete TH of **n** in 90 min at S/C = 10000 (entry 19). Under these conditions, selective reduction occurred only at the carbonyl group. The TH of the conjugated C═C bond began after longer reaction times, affording 40% of citronellol in 30 h, at **n**/**8** = 1000. With **8**, **h** was completely converted in 30 min with 75% of (−)-menthol at S/C = 1000, whereas at S/C = 10000 only 81% conversion was attained in 56 h (entries 16 and 17). Complex **9** promoted the TH of benzophenone **d** with complete formation of benzhydrol in 40 (S/C = 10000, TOF = 32000 $h^{-1}$) and 60 min (S/C = 25000, TOF = 25000 $h^{-1}$; entries 22 and 23), whereas with **10**, substrate **d** was reduced in 30 min (94% conv) at S/C = 1000 (entry 25). Complexes **9** and **10** efficiently catalyzed the TH of aldehydes. Benzaldehyde **j** was converted by **10** in 1 h at S/C = 1000 (entry 26), whereas the derivative **9** quantitatively reduced 4-bromobenzaldehyde **k** in 10 and 30 min at S/C = 10000 and 25000, respectively, with TOF up to 80000 $h^{-1}$ (entries 20 and 21). Highly chemoselective TH of (*E*)-2-methylcinnamaldehyde **l** was achieved employing **9** (S/C = 1000) in 40 min, leading to 93% of (*E*)-2-methylcinnamol (entry 24).

Complexes **1−11** were also studied in the HY of several ketones (2 M) at 30 bar of $H_2$ pressure at 70 °C in ethanol and methanol in the presence of KO*t*Bu at S/C up to 10000 (Scheme 6).

The dicarbonyl H*CNN* complexes **1−3** with 5 mol % KO*t*Bu showed no catalytic activity in the HY of **a**, as for the TH reactions. Addition of 2 equiv of $PPh_3$ or $PCy_3$ to **1** (S/C = 2000) in ethanol led to 34% and 46% conversion, respectively, after 16 h (Table 3; entries 1 and 2). Interestingly, quantitative conversion was attained in methanol with $PCy_3$ using KO*t*Bu or KOH as base (entries 3 and 4). A similar behavior was observed with the benzo[*h*]quinoline derivatives **2** and **3** in the presence of $PCy_3$, affording quantitative reduction of **a** in methanol and poor conversion in ethanol (entries 5 and 6 and Table S3 in the Supporting Information). The monocarbonyl complex **5** led to 63% conversion of **a** in methanol (16 h), whereas with **6** quantitative formation of 1-phenylethanol was obtained (entries 7 and 8). Conversely, the pincer *CNN* derivatives **9−11** showed lower activity, with better results in ethanol with respect to methanol. Complex **9** in the presence of 2 mol % KO*t*Bu gave 61% conversion of **a** in ethanol and 25% in methanol (16 h), and similar results were observed for **10** and **11** (Table S3 in the Supporting Information).

Complex **5** was tested in the HY of aryl methyl ketones with different electronic properties (Scheme 6). Benzophenone **d** was quantitatively converted to benzhydrol (99%) in 16 h (S/**5** = 500; Table 3, entry 9). The HY of 2′-methylacetophenone **o** led to 46% of conversion with a S/C = 10000 (entry 10), whereas 2′-chloroacetophenone **p** and 4′-nitroacetophenone **r** were quantitatively hydrogenated to the corresponding alcohols in the presence of 5 mol % KO*t*Bu (entries 11 and 13). In addition, 4′-methoxyacetophenone **q** afforded complete conversion at S/**5** = 500 (entry 12), while benzoin **s** gave 63% of 1,2-diphenyl-1,2-ethanediol at S/**5** = 10000, possibly due to



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

the chelate effect exerted by the diol product, resulting in catalyst poisoning (entry 14). Therefore, these data indicated that complex **5** displays a higher activity for methyl aryl ketones containing Cl and $NO_2$ electron-withdrawing groups (**p**, **r**) with respect to acetophenone **a** and the corresponding Me and OMe derivatives (**o**, **q**).

As regards the mechanism of the TH and HY reactions involving ruthenium complexes, catalytically active mono- or dihydride Ru species are generally formed from Ru−X (X = Cl, carboxylate) precursors, by reaction with alkoxides or $H_2$.[17,59] In the TH with 2-propanol the Ru−H species are generated by formation of acetone via an inner-sphere mechanism from a Ru−O*i*Pr complex. When a $NH_2$ moiety is present cis to the Ru−X center, the Ru−H species may be formed from a 16-electron Ru−amide complex and alcohol through an outer-sphere mechanism[60] or a Ru−amine/alkoxide.[6a,c,55,60a,61] Regarding the HY reactions, the Ru−H species are obtained through a dihydrogen splitting from a labile Ru−X precursor in basic alcohol (inner sphere) or from a 16-electron Ru−amide[6a,c] or Ru−amine/alkoxide species (outer sphere).[62]

Therefore, is it reasonable that, in the TH promoted by the pincer complexes **9**−**11**, the reaction occurs through substitution of the chloride with the isopropoxide, which leads to the corresponding catalytically active hydride [RuH(*CNN*)(CO)($PPh_3$)]. This process is in line with the mechanistic studies carried out on the analogous [RuX(*CNN*)(PP)] (X = Cl, H; H*CNN* = Hamtp; PP = dppb, (*S*,*S*)-skewphos),[55,61a] in which the $NH_2$ function accelerates TH and HY reactions. Using the monocarbonyl phosphine derivatives **5**−**8**, pincer [RuX(*CNN*)(CO)(P)] (X = Cl, H) can also be formed via cyclometalation under catalytic conditions. With the bidentate dicarbonyl ruthenium derivatives **1**−**3**, it is likely that, in the presence of an added phosphine, the first step in catalysis is the displacement of the HCNN ligand with $PR_3$, followed by CO elimination, coordination of the HCNN ligand, and cyclometalation, affording [RuX(*CNN*)(CO)(P)] species, a behavior which has also been observed for the [RuCl(*p*-cymene)(Hamtp)]Cl/phosphine catalytic system.[50] Control $^{31}P\{^1H\}$ NMR experiments showed that reaction of **1** with $PCy_3$ (2 equiv) at room temperature in $CDCl_3$ afforded *cis*,*trans*,*cis*-[$RuCl_2(PCy_3)_2(CO)_2$] ($\delta$ 27.7),[63] in a small amount, as result of Hamtp displacement. Heating of this solution at 90 °C (12 h) led to an increase in the dicarbonyl derivative, with the formation of the monocarbonyl *cis*,*trans*-[$RuCl_2(PCy_3)_2(CO)$] ($\delta$ 34.5), in addition to the cyclometalated species [RuCl(amtp)($PCy_3$)(CO)] (see the Supporting Information). Conversely, reaction of *cis*,*trans*,*cis*-[$RuCl_2(PCy_3)_2(CO)_2$] with Hamtp in 2-propanol at reflux (2 h) and in the presence of the base $NEt_3$ led to the formation of several species, including *trans*,*cis*-[$RuHCl(PCy_3)_2(CO)_2$] and uncharacterized ruthenium hydride species, in addition to [RuCl(amtp)($PCy_3$)(CO)], as inferred from $^1H-^1H$ COSY and $^{13}C\{^1H\}$ NMR measurements.[64] It is worth noting that for these types of ruthenium carbonyl complexes the use of the bulky and strongly basic phosphine $PCy_3$ gave better catalytic performance, with respect to $PPh_3$.[65] In addition, bulky ketones, such as pinacolone, pivalophenone, and camphor, were reduced efficiently with the **1**/$PCy_3$ system, which appeared superior with respect to the diphosphine derivatives [RuCl(*CNN*)(PP)][10e,14b] and to the well-known arene complexes [($\eta^6$-arene)RuCl($H_2$NCHPhCHPhNTs)].[66] This is likely due to the flatness of the pincer carbonyl system, allowing an easy access of the substrate to the metal hydride. Furthermore, these carbonyl complexes showed comparable or better performance with respect to [RuCl(*CNN*)(PP)] for the reduction of commercial grade aldehydes, with S/C values of up to 25000.[16b] Finally, employment of H*CNN* ligands afforded extremely active and productive catalysts with respect to the bidentate ampy derivatives, **1a**/$PCy_3$ and *trans*-[$RuCl_2$(ampy)($PPh_3$)(CO)],[25a] on account of the formation of more robust pincer complexes.

## CONCLUDING REMARKS

In conclusion, we reported the synthesis of bidentate H*CNN* *trans*-[$RuX_2$(H*CNN*)(L)(CO)] (X = Cl, OAc) and pincer *CNN* [RuCl(*CNN*)(L)(CO)] (H*CNN* = Hamtp, Hambq, $Hambq^{Ph}$; L = CO, $PPh_3$) carbonyl complexes starting from $RuCl_3{\cdot}xH_2O$, [$RuCl_2(CO)_2]_n$, [$RuCl_2(PPh_3)_2$(dmf)(CO)], [$Ru(OAc)_2(PPh_3)_2$(CO)], and *cis*-[RuCl(*CNN*)($PPh_3$)$_2$] precursors. The monocarbonyl phosphine complexes and the dicarbonyl derivatives, in the presence of phosphine ($PPh_3$ or $PCy_3$), efficiently catalyzed the TH of ketones, including bulky substrates, and the chemoselective TH of unsaturated aldehydes in 2-propanol at reflux at S/C = 1000−100000 and TOF values of up to 100000 $h^{-1}$. In addition, these complexes were active catalysts for the HY of ketones ($H_2$, 30 bar) in MeOH and EtOH at S/C values of up to 10000. Formation of cyclometalated ruthenium carbonyl/phosphine species represents a key issue for achieving highly productive catalysts. Studies are ongoing to extend this synthetic protocol to the preparation of *CNN* pincer carbonyl complexes and apply these new systems for catalytic C−H activation organic transformations.

## EXPERIMENTAL SECTION

All reactions were carried out under an argon atmosphere using standard Schlenk techniques. The solvents were dried by standard methods and distilled under argon before use. The ruthenium compound $RuCl_3{\cdot}xH_2O$ ($x$ = 2.5) was purchased from Alfa/Aesar, whereas all other chemicals were acquired from Aldrich and Strem and used without further purification. The H*CNN* ligands Hamtp,[10d] Hambq,[14b] and $Hambq^{Ph}$ [10a] and the complexes [$RuCl_2(CO)_2]_n$,[67] [$RuCl_2$(dmf)($PPh_3$)$_2$(CO)],[68] [$Ru(OAc)_2(PPh_3)_2$(CO)],[69] *cis*-[RuCl(amtp)($PPh_3$)$_2$],[50] and *cis*-[RuCl(ambq)($PPh_3$)$_2$][14b] were prepared according to the literature procedures. NMR measurements were recorded on a Bruker AC 200 spectrometer,and the chemical shifts, in ppm, were relative to TMS for $^1H$ and $^{13}C\{^1H\}$ and 85% $H_3PO_4$ for $^{31}P\{^1H\}$. Elemental analyses (C, H, N) were carried out with a Carlo Erba 1106 elemental analyzer, whereas the GC analyses were performed with a Varian GP-3380 gas chromatograph equipped with a MEGADEX-ETTBDMS-$\beta$ chiral column of 25 m length, column pressure 5 psi, hydrogen as carrier gas, and flame ionization detector (FID). The injector and detector temperature was 250 °C, with initial $T$ = 95 °C ramped to 140 °C at 3 °C/$min^{-1}$ for a total of 20 min of analysis. The $t_R$ value of acetophenone was 7.03 min, while the $t_R$ values of (*R*)- and (*S*)-1-phenylethanol were 9.93 and 10.15 min, respectively.

**Synthesis of *trans*,*cis*-[$RuCl_2$(Hamtp)(CO)$_2$] (1).** $RuCl_3{\cdot}xH_2O$ (83.2 mg, 0.33 mmol) was added to formic acid (6 mL, 0.16 mol), and the suspension was stirred in a sealed tube at 110 °C for 2 h, until the mixture turned yellow and homogeneous, giving [$RuCl_2(CO)_2]_n$. The solvent was evaporated under reduced pressure, and the residue was dissolved in distilled ethanol (6 mL). After addition of the ligand Hamtp (78.1 mg, 0.39 mmol, 1.2 equiv), the solution was stirred at 80 °C overnight and then the solvent was evaporated under reduced pressure. The residue was dissolved in chloroform (2 mL), and the solution was stirred for 1 h at room temperature. The complex was precipitated by addition of diethyl ether (10 mL). After filtration, the



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

solid was washed with diethyl ether (2 × 5 mL) and *n*-pentane (5 mL) and dried under reduced pressure. Yield: 105.3 mg (75%). Anal. Calcd for $C_{15}H_{14}Cl_2N_2O_2Ru$: C, 42.27; H, 3.31; N, 6.57. Found: C, 42.19; H, 3.26; N, 6.59. IR (Nujol): 2067 (s), 1998 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CDCl_3$, 20 °C): $\delta$ 7.79 (t, $^3J(H,H)$ = 7.7 Hz, 1H; aromatic proton), 7.54 (d, $^3J(H,H)$ = 8.2 Hz, 2H; aromatic protons), 7.45−7.29 (m, 4H; aromatic protons), 4.78 (t, $^3J(H,H)$ = 6.2 Hz, 2H; $CH_2N$), 4.19 (t, $^3J(H,H)$ = 5.9 Hz, 2H; $NH_2$), 2.45 (s, 3H; $CH_3$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CDCl_3$, 20 °C): $\delta$ 195.5 (s; CO), 190.3 (s; CO), 164.8 (s; NCC), 159.7 (s; $NCCH_2$), 140.5−120.2 (m, aromatic carbon atoms), 51.2 (s, $CH_2N$), 21.5 (s; $CH_3$).

**Synthesis of *trans,cis*-[$RuCl_2$(ampy)(CO)$_2$] (1a).** $[RuCl_2(CO)_2]_n$ (50.8 mg, 0.22 mmol) was suspended in an ethanol/water mixture (3:1; 4 mL) and ampy (28 mL, 0.27 mmol, 1.2 equiv) was added to the slurry. The mixture was stirred at reflux for 2 h, and then the solvent was removed under reduced pressure. The residue was dissolved in dichloromethane (1 mL) and stirred for 30 min at room temperature. Addition of diethyl ether (5 mL) afforded the precipitation of the complex, which was filtered, washed with diethyl ether (2 × 2 mL) and *n*-pentane (2 mL) and finally dried under reduced pressure. Yield 57.6 mg (78%). Anal. Calcd for $C_8H_8Cl_2N_2O_2Ru$: C, 28.59; H, 2.40; N, 8.33. Found: C, 28.55; H, 2.36; N, 8.39. IR (Nujol): 2054 (s), 1991 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CDCl_3$, 20 °C): $\delta$ 8.94 (dd, $^3J(H,H)$ = 6.0 Hz, $^4J(H,H)$ = 1.5 Hz, 1H; *o*-$C_5H_4N$), 7.90 (td, $^3J(H,H)$ = 7.8 Hz, $^4J(H,H)$ = 1.4 Hz, 1H; *p*-$C_5H_4N$), 7.52−747 (m, 2H; *m*-$C_5H_4N$ protons), 4.73 (t, $^3J(H,H)$ = 5.9 Hz, 2H; $CH_2N$), 4.22 (t, $^3J(H,H)$ = 5.2 Hz, 2H; $NH_2$). $^{13}C\{^1H$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 195.9 (s; CO), 192.7 (s; CO), 160.2 (s; $NCCH_2$), 153.0 (s; C(6) of Py), 139.6 (s; C(4) of Py), 125.2 (s; C(3) of Py), 122.5 (s; C(5) of Py), 50.6 (s; $CH_2N$).

**Synthesis of *trans,cis*-[$RuCl_2$(Hambq)(CO)$_2$] (2).** $[RuCl_2(CO)_2]_n$ (203 mg, 0.89 mmol) was reacted with the ligand Hambq (202.0 mg, 0.97 mmol, 1.1 equiv) in ethanol (10 mL), and the suspension was stirred at 80 °C overnight. The solvent was removed under reduced pressure, and the residue was dissolved in dichloromethane (4 mL). The solution was stirred at room temperature for 4 h, and then the volume was reduced to about 1 mL, with evaporation of the solvent under vacuum. The complex was precipitated by addition of diethyl ether (10 mL). The obtained solid was filtered, washed with diethyl ether (2 × 5 mL) and *n*-pentane (5 mL), and dried under reduced pressure. Yield: 190 mg (49%). Anal. Calcd for $C_{16}H_{12}Cl_2N_2O_2Ru$: C, 44.05; H, 2.77; N, 6.42. Found: C, 44.10, H, 2.78; N, 6.38. IR (Nujol): 2059 (s), 1985 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 9.07 (dd, $^3J(H,H)$ = 4.4 Hz, $^4J(H,H)$ = 1.0 Hz, 1H; aromatic proton), 8.29 (d, $^3J(H,H)$ = 8.3 Hz, 1H; aromatic proton), 8.11−7.41 (m, 6H; aromatic protons), 4.59 (m, 2H; $CH_2N$), 3.68 (br s, 2H; $NH_2$). $^1H$ NMR (200.1 MHz, tetrachloroethane-$d_2$, 20 °C): $\delta$ 9.04 (d, $^3J(H,H)$ = 4.5 Hz, 1H; aromatic proton), 8.23 (d, $^3J(H,H)$ = 7.5 Hz, 1H; aromatic proton), 8.13−7.03 (m, 6H; aromatic protons), 4.61 (m, 2H; $CH_2N$), 3.67 (br s, 2H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, tetrachloroethane-$d_2$, 20 °C): $\delta$ 200.0 (s; CO), 190.4 (s; CO), 160.0 (s; NCC), 156.5 (s; $NCCH_2$), 150.6−117.2 (m; aromatic carbon atoms), 52.3 (s; $CH_2N$).

**Synthesis of *trans,cis*-[$RuCl_2$(Hambq$^{Ph}$)(CO)$_2$] (3).** $[RuCl_2(CO)_2]_n$ (227 mg, 1.00 mmol) suspended in ethanol (10 mL) was reacted with HCl·Hambq$^{Ph}$ (353 mg, 1.10 mmol, 1.1 equiv). The suspension was stirred at 80 °C overnight, and the solvent was evaporated under reduced pressure. The residue was dissolved in dichloromethane (4 mL), and the mixture was stirred at room temperature for 4 h. The solution was concentrated to about 1 mL, with removal of the solvent under reduced pressure, and the complex was precipitated by addition of diethyl ether (10 mL). The obtained solid was filtered, washed with diethyl ether (2 × 5 mL) and *n*-pentane (5 mL), and dried under reduced pressure. Yield: 370 mg (72%). Anal. Calcd for $C_{22}H_{16}Cl_2N_2O_2Ru$: C, 51.57; H, 3.15; N, 5.47. Found: C, 51.49; H, 3.22; N, 5.51. IR (Nujol): 2055 (s), 1984 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 9.42 (d, $^3J(H,H)$ = 7.4 Hz, 1H; aromatic proton), 8.22−7.03 (m, 11H; aromatic protons), 4.68 (m, 2H; $CH_2N$), 3.87 (m, 2H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 201.2 (s; CO), 194.4 (s; CO), 161.7 (s; NCC), 157.2 (s; $NCCH_2$), 150.4−118.2 (m; aromatic carbon atoms), 46.4 (s; $CH_2N$).

**Synthesis of *cis*-[RuCl(amtp)(CO)$_2$] (4).** *Method A.* *trans,cis*-$[RuCl_2(Hamtp)(CO)_2]$ (**1**; 76.3 mg, 0.18 mmol) was suspended in *n*-butanol (5 mL), and triethylamine (250 μL, 1.79 mmol, 10 equiv) was added. The mixture was heated at 110 °C overnight, giving a brown solution. The solvent was removed under reduced pressure, and the residue was dissolved in dichloromethane (5 mL) and stirred with $K_2CO_3$ (112 mg, 0.81 mmol, 4.5 equiv) for 2 h at room temperature. The mixture was filtered, the filtrate was concentrated to about 0.5 mL, and the product was precipitated by addition of *n*-pentane (5 mL). The solid was filtered, washed with diethyl ether (2 × 2 mL) and *n*-pentane (2 × 5 mL), and dried under reduced pressure. Yield: 41.6 mg (58%). Anal. Calcd for $C_{15}H_{13}ClN_2O_2Ru$: C, 46.22; H, 3.36; N, 7.19. Found: C, 46.25; H, 3.30; N, 7.11. IR (Nujol): 2028 (s), 1958 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CDCl_3$, 20 °C): $\delta$ 7.76 (d, $^3J(H,H)$ = 7.4 Hz, 1H; aromatic proton), 7.73−7.63 (m, 1H; aromatic proton), 7.59 (d, $^3J(H,H)$ = 8.0 Hz, 1H; aromatic proton), 7.56−7.44 (m, 1H; aromatic proton), 7.10 (d, $^3J(H,H)$ = 7.0 Hz, 1H; aromatic proton), 6.88 (d, $^3J(H,H)$ = 7.7 Hz, 1H; aromatic proton), 4.65 (dd, $^2J(H,H)$ = 16.4 Hz, $^3J(H,H)$ = 6.5 Hz, 1H; $NCH_2$), 4.41 (m, 1H; $NCH_2$), 4.06 (m, 1H; $NH_2$), 3.46 (m, 1H; $NH_2$), 2.32 (s, 3H; $CH_3$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CDCl_3$, 20 °C): $\delta$ 200.4 (s, CO), 194.0 (s, CO), 164.2 (s, CRu), 162.6 (s, NCC), 157.6 (s, $NCCH_2$), 142.8−117.1 (m; aromatic carbon atoms), 52.3 (s; $NCH_2$), 21.7 (s; $CH_3$).

*Method B.* $RuCl_3{\cdot}xH_2O$ (128.8 mg, 0.51 mmol) was suspended in formic acid (7 mL, 0.186 mol), and the slurry was stirred at 110 °C for 2 h. The solvent was evaporated under reduced pressure, and the residue, dissolved in *n*-butanol (7 mL), was reacted with the ligand Hamtp (111.0 mg, 0.56 mmol, 1.1 equiv) and triethylamine (1.4 mL, 10.0 mmol, 20 equiv). The solution was stirred at 110 °C overnight, and then the solvent was evaporated under reduced pressure. The residue was dissolved in $CHCl_3$ (2 mL), stirred with $K_2CO_3$ (320 mg, 2.32 mmol, 4.5 equiv) for 2 h at room temperature, and filtered. The filtrate was concentrated to about 1 mL, and the complex was precipitated by addition of diethyl ether (10 mL). The obtained solid was filtered, washed with diethyl ether (2 × 3 mL) and *n*-pentane (3 mL), and finally dried under reduced pressure. Yield: 61.2 mg (30%).

**Synthesis of *trans*-[$RuCl_2$(Hamtp)(PPh$_3$)(CO)] (5).** $[RuCl_2(dmf)(PPh_3)_2(CO)]$ (282.3 mg, 0.36 mmol), suspended in chloroform (15 mL), was reacted with the ligand Hamtp (78.4 mg, 0.40 mmol, 1.1 equiv), and the mixture was stirred at 60 °C overnight. The obtained solution was concentrated to about 1 mL by solvent evaporation under vacuum. The complex was precipitated by addition of *n*-pentane (10 mL). The obtained solid was filtered, washed with diethyl ether (2 × 5 mL) and *n*-pentane (5 mL), and dried under reduced pressure. Yield: 160.3 mg (68%). Anal. Calcd for $C_{32}H_{29}Cl_2N_2OPRu$: C, 58.19; H, 4.43; N, 4.24. Found: C, 58.20; H, 4.40; N, 4.28. IR (Nujol): 1947 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CDCl_3$, 20 °C): $\delta$ 7.69 (m, 10H; aromatic protons), 7.37 (m, 11H; aromatic protons), 7.15 (d, $^3J(H,H)$ = 8.2 Hz, 1H; aromatic proton), 4.50 (t, $^3J(H,H)$ = 6.0 Hz, 2H; $NCH_2$), 3.13 (t, $^3J(H,H)$ = 5.9 Hz, 2H; $NH_2$), 2.49 (s, 3H; $CH_3$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CDCl_3$, 20 °C): $\delta$ 200.5 (d, $^2J(C,P)$ = 21.5 Hz; CO), 165.3 (s; NCC), 161.2 (d, $^3J(C,P)$ = 1.0 Hz; $NCCH_2$), 140.3−119.6 (m; aromatic carbon atoms), 50.1 (d, $^3J(C,P)$ = 2.8 Hz; $CH_2N$), 21.5 (s; $CH_3$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CDCl_3$, 20 °C): $\delta$ 54.5.

**Synthesis of *trans*-[$RuCl_2$(Hambq)(PPh$_3$)(CO)] (6).** $[RuCl_2(dmf)(PPh_3)_2(CO)]$ (365 mg, 0.46 mmol), suspended in *n*-butanol (5 mL), was reacted with the ligand Hambq (208 mg, 1.00 mmol, 2.2 equiv). The mixture was stirred at 130 °C overnight, and then the solvent was evaporated under reduced pressure and the residue was dissolved in chloroform (1 mL). The solution was stirred for 1 h at room temperature, and the complex was precipitated by addition of diethyl ether (10 mL). The solid was filtered, washed with diethyl ether (2 × 3 mL) and *n*-pentane (3 mL), and finally dried under reduced pressure. Yield: 291 mg (93%). Anal. Calcd for $C_{33}H_{27}Cl_2N_2OPRu$: C, 59.11; H, 4.06; N, 4.18. Found: C, 59.20; H,


DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

4.10; N, 4.16. IR (Nujol): 1920 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 9.29 (d, $^3J(H,H)$ = 7.2 Hz, 1H; aromatic proton), 8.10−6.87 (m, 21H; aromatic protons), 6.72 (d, $^3J(H,H)$ = 8.3 Hz, 1H; aromatic proton), 4.27 (m, 2H; $CH_2N$), 3.91 (m, 2H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 200.4 (d, $^2J(C,P)$ = 18.4 Hz; CO), 160.3 (s; NCC), 155.0 (s; $NCCH_2$), 142.6−116.7 (m; aromatic carbon atoms), 49.5 (s; $CH_2N$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 53.4.

**Synthesis of *trans*-[$RuCl_2$(Hambq$^{Ph}$)($PPh_3$)(CO)] (7).** [$RuCl_2$(dmf)($PPh_3$)$_2$(CO)] (245 mg, 0.31 mmol) was reacted with HCl·Hambq$^{Ph}$ (159 mg, 0.50 mmol, 1.6 equiv) and tributylamine (0.5 mL, 2.1 mmol, 6.8 equiv) in *n*-butanol (5 mL), and the mixture was stirred at 130 °C overnight. The solvent was evaporated under reduced pressure, and the residue was dissolved in chloroform (3 mL). After addition of $K_2CO_3$ (200 mg, 1.45 mmol, 4.7 equiv), the mixture was stirred for 2 h at room temperature. The suspension was filtered, and the solution was concentrated to about 1 mL by evaporation of the solvent under reduced pressure. The complex was precipitated by addition of diethyl ether (10 mL), filtered, washed with diethyl ether (2 × 3 mL) and *n*-pentane (3 mL), and finally dried under reduced pressure. Yield: 101 mg (44%). Anal. Calcd for $C_{39}H_{31}Cl_2N_2OPRu$: C, 62.74; H, 4.19; N, 3.75. Found: C, 62.66; H, 4.10; N, 3.82. IR (Nujol): 1924 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 9.08 (m, 1H; aromatic proton), 7.92−6.56 (m, 27H; aromatic protons), 4.16 (dd, $^2J(H,H)$ = 10.3 Hz, $^3J(H,H)$ = 4.9 Hz, 2H; $CH_2N$), 3.88 (m, 2H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 200.5 (d, $^2J(C,P)$ = 17.5 Hz; CO), 159.9 (s; NCC), 155.1 (s; $NCCH_2$), 148.7−117.2 (m; aromatic carbon atoms), 49.5 (s; $CH_2N$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 53.5.

**Synthesis of *trans*-[$Ru(OAc)_2$(Hamtp)($PPh_3$)(CO)] (8).** [Ru($OAc)_2$($PPh_3$)$_2$(CO)] (100.3 mg, 0.13 mmol) and the ligand Hamtp (28.3 mg, 0.14 mmol, 1.1 equiv) were suspended in toluene (5 mL), and the mixture was stirred at 110 °C for 2 days. The resulting solution was concentrated to almost 0.5 mL, the solvent was evaporated under reduced pressure, and the complex was precipitated by addition of *n*-pentane (7 mL). The solid was filtered, washed with *n*-heptane (2 × 5 mL) and diethyl ether (2 × 3 mL), and dried under reduced pressure. Yield: 37.1 mg (40%). Anal. Calcd for $C_{36}H_{35}N_2O_5PRu$: C, 61.10; H, 4.98; N, 3.96. Found: C, 61.02; H, 5.03; N, 3.89. IR (Nujol): 1914 (s) ($\nu_{C\equiv O}$), 1597 (s) and 1572 $cm^{-1}$ (s) ($\nu_{C=O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 8.17 (d, $^3J(H,H)$ = 7.9 Hz, 1H; $NH_2$), 7.79−7.60 (m, 6H; aromatic protons), 7.46−7.37 (m, 6H; aromatic protons), 7.30−7.17 (m, 7H; aromatic protons), 7.06 (m, 1H; aromatic proton), 6.91 (d, $^3J(H,H)$ = 8.4 Hz, 1H; aromatic proton), 6.64 (dd, $^3J(H,H)$ = 12.3 Hz, $^3J(H,H)$ = 7.8 Hz, 1H; aromatic proton), 4.41 (dd, $^2J(H,H)$ = 16.6 Hz, $^3J(H,H)$ = 6.5 Hz, 1H; $CH_2N$), 4.21 (m, 1H; $CH_2N$), 2.14 (s, 3H; $CH_3$), 2.07 (s, 3H; $CH_3CO$), 1.57 (m, 1H; $NH_2$), 1.23 (s, 3H; $CH_3CO$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 202.9 (d, $^2J(C,P)$ = 17.4 Hz; CO), 180.5 (s; $CH_3CO$), 177.7 (s; $CH_3CO$), 163.5 (s; NCC), 161.0 (s; $NCCH_2$), 146.5−116.7 (m; aromatic carbon atoms), 52.2 (d, $^3J(C,P)$ = 2.6 Hz; $CH_2N$), 25.3 (s; $CH_3CO$), 25.0 (s; $CH_3CO$), 21.6 (s; $CH_3$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 54.4.

**Synthesis of [RuCl(amtp)($PPh_3$)(CO)] (9).** *cis*-[RuCl(amtp)($PPh_3$)$_2$] (251.9 mg, 0.29 mmol) was suspended in dichloromethane (5 mL), and the mixture was stirred under a CO atmosphere (1 atm) overnight at room temperature. The solvent was evaporated under reduced pressure, and the residue was purified by flash chromatography, using dichloromethane/diethyl ether as eluent (gradient 9/1 to 1/1). Yield: 106 mg (59%). Anal. Calcd for $C_{32}H_{28}ClN_2OPRu$: C, 61.59; H, 4.52; N, 4.49. Found: C, 61.64; H, 4.61; N, 4.56. IR (Nujol): 1905 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 7.78 (ddd, $^3J(H,H)$ = 9.9 Hz, $^3J(H,H)$ = 6.7 Hz, $^4J(H,H)$ = 2.9 Hz, 2H; aromatic protons), 7.57−7.15 (m, 17H; aromatic protons), 6.69 (dd, $^3J(H,H)$ = 6.6 Hz, $^3J(H,H)$ = 1.9 Hz, 1H; aromatic proton), 6.62 (ddd, $^3J(H,H)$ = 8.0 Hz, $^4J(H,H)$ = 1.7 Hz, $^4J(H,H)$ = 0.6 Hz, 1H; aromatic proton), 4.25 (dd, $^2J(H,H)$ = 16.2 Hz, $^3J(H,H)$ = 6.3 Hz, 1H; $CH_2N$), 3.86 (dd, $^2J(H,H)$ = 16.6 Hz, $^3J(H,H)$ = 8.9 Hz, 1H; $NH_2$), 3.41 (ddd, $^2J(H,H)$= 16.5 Hz, $^3J(H,H)$ = 10.0 Hz, $^3J(H,H)$ = 6.5 Hz, 1H; $CH_2N$), 2.79 (dd, $^2J(H,H)$ = 8.6 Hz, $^3J(H,H)$ = 6.6 Hz, 1H; $NH_2$), 2.14 (s, 3H; $CH_3$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 207.5 (d, $^2J(C,P)$ = 18.2 Hz; CO), 176.3 (d, $^2J(C,P)$ = 12.3 Hz; CRu), 162.2 (s; NCC), 157.2 (s; $NCCH_2$), 145.4−116.4 (m; aromatic carbon atoms), 51.2 (d, $^3J(C,P)$ = 5.3 Hz; $CH_2N$), 21.7 (s; $CH_3$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 57.6.

**Synthesis of [RuCl(ambq)($PPh_3$)(CO)] (10).** Complex **10** was prepared by following the procedure used for **9**, employing *cis*-[RuCl(ambq)($PPh_3$)$_2$] (226 mg, 0.26 mmol) in place of *cis*-[RuCl(amtp)($PPh_3$)$_2$]. Yield: 132 mg (80%). Anal. Calcd for $C_{33}H_{26}ClN_2OPRu$: C, 62.51; H, 4.13; N, 4.42. Found: C, 62.55; H, 4.10; N, 4.37. IR (Nujol): 1922 (s) $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 8.02 (d, $^3J(H,H)$ = 8.2 Hz, 1H; aromatic proton), 7.90 (dt, $^3J(H,H)$ = 6.6 Hz, $^4J(H,H)$ = 1.3 Hz, 2H; aromatic protons), 7.45−6.98 (m, 19H; aromatic protons), 4.51 (dd, $^2J(H,H)$ = 17.3 Hz, $^3J(H,H)$ = 5.9 Hz, 1H; $CH_2N$), 4.03 (dd, $^2J(H,H)$ = 17.4 Hz, $^3J(H,H)$ = 8.4 Hz, 1H; $NH_2$), 3.70 (ddd, $^2J(H,H)$ = 16.7 Hz, $^3J(H,H)$ = 6.3 Hz, $^3J(H,H)$ = 3.8 Hz, 1H; $CH_2N$), 2.86 (pseudo t, $J(H,H)$ = 8.4 Hz, 1H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$): $\delta$ 207.8 (d, $^2J(C,P)$ = 17.5 Hz; CO), 172.1 (d, $^2J(C,P)$ = 12.8 Hz; CRu), 156.0 (s; NCC), 150.6 (s; $NCCH_2$), 142.4−116.6 (m; aromatic carbon atoms), 51.4 (s; $CH_2N$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 58.5.

**Synthesis of *cis*-[RuCl(ambq$^{Ph}$)($PPh_3$)$_2$] (11a).** The hydrochloride ligand HCl·Hambq$^{Ph}$ (183.5 mg, 0.57 mmol) and $NEt_3$ (0.35 mL, 2.59 mmol) were added to [$RuCl_2$($PPh_3$)$_3$] (500 mg, 0.52 mmol) in 2-propanol (5 mL), and the mixture was heated under reflux for 2 h. The resulting solution was concentrated (1 mL), and addition of *n*-pentane (5 mL) afforded an orange precipitate. The solid was filtered, washed with *n*-pentane (2 × 5 mL), and dried under reduced pressure. The product was recrystallized from methanol (3 mL). Yield: 432 mg (88%). Anal. Calcd for $C_{56}H_{45}ClN_2P_2Ru$: C, 71.22; H, 4.80; N, 2.97. Found: C, 71.11; H, 4.73; N, 3.02. $^1H$ NMR (200.1 MHz, $CDCl_3$, 20 °C): $\delta$ 8.36 (dd, $^3J(H,H)$ = 5.0 Hz, $^4J(H,H)$ = 2.6 Hz, 1H; aromatic proton), 7.80−6.79 (m, 34H; aromatic protons), 6.69 (t, $^3J(H,H)$ = 6.8 Hz, 6H; aromatic protons), 4.31 (dd, $^2J(H,H)$ = 16.0 Hz, $^3J(H,H)$ = 3.6 Hz, 1H; $CH_2N$), 4.02 (m, 1H; $NH_2$), 3.61 (dt, $^2J(H,H)$ = 16.1 Hz, $^3J(H,H)$ = 7.6 Hz, 1H; $CH_2N$), 3.02 (m, 1H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CDCl_3$, 20 °C): $\delta$ 177.9 (d, $^2J(C,P)$ = 3.9 Hz; CRu), 161.3 (d, $^3J(C,P)$ = 1.9 Hz; $NCCH_2$), 155.1(s; NCC), 142.1−116.9 (m; aromatic carbon atoms), 50.8 (d, $^3J(C,P)$ = 2.8 Hz; $CH_2N$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CDCl_3$, 20 °C): $\delta$ 57.3 (d, $^2J(P,P)$ = 33.7 Hz), 50.8 (d, $^2J(P,P)$ = 33.7 Hz).

**Synthesis of [RuCl(ambq$^{Ph}$)($PPh_3$)(CO)] (11).** Complex **11** was prepared by following the procedure used for **9**, employing *cis*-[RuCl(ambq$^{Ph}$)($PPh_3$)$_2$] (**11a**; 119.8 mg, 0.13 mmol) in place of *cis*-[RuCl(amtp)($PPh_3$)$_2$]. Yield: 76.6 mg (83%). Anal. Calcd for $C_{39}H_{30}ClN_2OPRu$: C, 65.96; H, 4.26; N, 3.94. Found: C, 66.01; H, 4.33; N, 4.02. IR (Nujol): 1920 $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 7.96 (dd, $^3J(H,H)$ = 6.0 Hz, $^4J(H,H)$ = 1.0 Hz, 1H; aromatic proton), 7.66 (d, $^3J(H,H)$ = 9.0 Hz, 1H; aromatic proton), 7.61−7.48 (m, 5H; aromatic protons), 7.44 (t, $^3J(H,H)$ = 2.6 Hz, 1H; aromatic proton), 7.36−7.30 (m, 2H; aromatic protons), 7.29−7.05 (m, 15H; aromatic protons), 7.03 (br s, 1H; aromatic proton), 4.57 (dd, $^2J(H,H)$ = 16.9 Hz, $^3J(H,H)$ = 6.7 Hz, 1H; $CH_2N$), 4.14 (dd, $^2J(H,H)$ = 17.4 Hz, $^3J(H,H)$ = 7.6 Hz, 1H; $NH_2$), 3.81 (dt, $^2J(H,H)$ = 16.4 Hz, $^3J(H,H)$ = 7.6 Hz, 1H; $CH_2N$), 2.99 (pseudo t, $J(H,H)$ = 7.9 Hz, 1H; $NH_2$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 208.0 (d, $^2J(C,P)$ = 17.4 Hz; CO), 172.6 (d, $^2J(C,P)$ = 12.8 Hz; CRu), 155.8 (s; NCC), 150.9 (s; $NCCH_2$), 148.7 (s; ipso-Ph), 142.7−117.2 (m; aromatic carbon atoms), 51.5 (s; $CH_2N$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 58.0.

**Synthesis of *trans*-[Ru(amtp)($PPh_3$)$_2$(CO)][$BAr^f_4$] (12).** Na[$BAr^f_4$] (71.0 mg, 0.0801 mmol) was added to [RuCl(amtp)($PPh_3$)(CO)] (**9**; 50.0 mg, 0.0801 mmol) and $PPh_3$ (21.0 mg, 0.0801 mmol) in dichloromethane (5 mL). The reaction mixture was stirred for 30 min at room temperature and filtered to remove NaCl. The obtained solution was concentrated (1 mL), and addition of *n*-heptane (5 mL) afforded a light yellow precipitate that was filtered, washed with


DOI: 10.1021/acs.organomet.8b00919
Organometallics XXXX, XXX, XXX−XXX

pentane (2 × 3 mL), and dried under reduced pressure. Yield: 108.5 mg (79%). Anal. Calcd for $C_{82}H_{55}BF_{24}N_2OP_2Ru$: C, 57.46; H, 3.23; N, 1.63. Found: C, 57.52; H, 3.27; N, 1.62. IR (Nujol): 1914 $cm^{-1}$ ($\nu_{C\equiv O}$). $^1H$ NMR (200.1 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 7.75 (m, 8H; aromatic protons), 7.58 (s, 4H; aromatic protons), 7.44−7.32 (m, 8H; aromatic protons), 7.30−7.20 (m, 11H; aromatic protons), 7.19−7.06 (m, 15H; aromatic protons), 6.62 (d, $^3J$(H,H) = 7.9 Hz, 1H; aromatic proton), 6.42 (dd, $^3J$(H,H) = 7.6 Hz, $^4J$(H,H) = 0.5 Hz, 1H; aromatic proton), 3.53 (t, $^3J$(H,H) = 6.5 Hz, 2H; $CH_2N$), 2.95 (m, 2H; $NH_2$), 2.04 (s, 3H; $CH_3$). $^{13}C\{^1H\}$ NMR (50.3 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 205.9 (t, $^2J$(C,P) = 15.7 Hz; CO), 169.4 (t, $^2J$(C,P) = 10.5 Hz; CRu), 162.1 (q, $^1J$(C,B) = 50.1 Hz; CB), 162.0 (s; NCC), 156.3 (s; $NCCH_2$), 144.6−116.8 (aromatic carbon atoms), 124.7 (q, $^1J$(C,F) = 271.8 Hz; $CF_3$), 50.6 (s; $CH_2N$), 21.7 (s; $CH_3$). $^{31}P\{^1H\}$ NMR (81.0 MHz, $CD_2Cl_2$, 20 °C): $\delta$ 35.5.

**Typical Procedure for TH of Ketones and Aldehydes.** The ruthenium catalyst solution used for TH was prepared by dissolving the complexes **1**−**12** and *cis,trans,cis*-$[RuCl_2(PCy_3)_2(CO)_2]$ (0.02 mmol) in 2-propanol (5 mL). The catalyst solution (250 μL, 1.0 μmol) and a 0.1 M solution of NaO*i*Pr (200 μL, 20 μmol) in 2-propanol were added subsequently to the ketone or aldehyde solution (1.0 mmol) in 2-propanol (final volume 10 mL), and the resulting mixture was heated under reflux. The reaction mixture was sampled by removing an aliquot of it, which was quenched by addition of diethyl ether (1/1 v/v), filtered over a short silica pad, and submitted to GC analysis. The base addition was considered as the start time of the reaction. The S/C molar ratio was 1000/1, whereas the base concentration was 2 mol % with respect to substrate (0.1 M). The same procedure was followed for TH reactions with other S/C values (in the range 1000−100000) or with different base concentrations (1−5 mol %), using the appropriate amount of catalysts, base, and 2-propanol.

**Typical Procedure for TH of Ketones and Aldehydes with in Situ Prepared Catalysts from 1−11 and *cis,trans,cis*-$[RuCl_2(PCy_3)_2(CO)_2]$.** The catalyst solutions were prepared by adding 2-propanol (5 mL) to the complexes **1**−**11** (0.02 mmol) and the corresponding ligand ($PPh_3$ or $PCy_3$, 0.04 mmol). The mixtures were stirred for 30 min at reflux. The solutions of the in situ formed catalyst were used in the TH reactions as described above.

In the case of *cis,trans,cis*-$[RuCl_2(PCy_3)_2(CO)_2]$, the ampy or Hamtp ligand was added to the ruthenium complex in 2-propanol (ligand/catalyst ratio 2) and the mixture was refluxed for 2 h. The solution of the in situ formed catalyst was used in the TH reactions as described above.

**Typical Procedure for HY of Ketones with 1−3, 5, 6, and 9−11.** The HY reactions were performed in an eight-vessel Endeavor Biotage apparatus. The vessels were charged with the ruthenium catalysts (2.5 μmol), loaded with 5 bar of $N_2$, and slowly vented (five times). The ketones (5 mmol), eventual ligand ($PPh_3$ or $PCy_3$, 5 μmol), and a KO*t*Bu solution (1 mL, 0.1 mmol, 0.1 M) in methanol or ethanol were added. Further addition of the solvent (methanol or ethanol) led to a 2 M ketone solution. The vessels were purged with $N_2$ and $H_2$ (three times each), and then the system was charged with $H_2$ (30 bar) and heated to 70 °C for the required time (16 h). The S/C molar ratio was 2000/1, whereas the base concentration was 2 mol %. A similar method was applied for the reactions with other S/C values (in the range 500−10000) or with different base concentrations (5 mol %), using the appropriate amount of catalysts, base, ligands (ligand/catalyst ratio 2), and solvent. The reaction vessels were then cooled to room temperature, vented, and purged three times with $N_2$. A drop of the reaction mixture was then diluted with 1 mL of methanol and analyzed by GC.

**Single-Crystal X-ray Crystallography Structure Determination of Compound 11.** Single crystals of complex **11** were obtained by slow cooling of a concentrated solution of the species in $CH_2Cl_2$. X-ray diffraction data were collected with a Bruker APEX-II κ-CCD diffractometer equipped with a rotating anode (Bruker AXS, FR591) by using graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). For additional details for the collection and refinement of data, see the Supporting Information.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.organomet.8b00919.

NMR data of the isolated complexes, X-ray crystallographic details of compound **11**, and catalytic results of the TH and HY reactions (PDF)

### Accession Codes

CCDC 1868440 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

## ■ AUTHOR INFORMATION


### Corresponding Author

*E-mail for W.B.: walter.baratta@uniud.it.

### ORCID

Alexander Pöthig: 0000-0003-4663-3949

Daniele Zuccaccia: 0000-0001-7765-1715

Walter Baratta: 0000-0002-2648-1848


### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

This work was supported by the Ministero dell'Università e della Ricerca (MIUR), PRIN 2015 program no. 20154X9ATP_005, and the Fellowship Program "Talents for an International House (TALENTS UP)" (seventh R&D FP: PEOPLE - Marie Curie Actions - COFUND) and AREA Consortium of Trieste for a fellowship for S.G. We thank Mr. Riccardo Bot for carrying out transfer hydrogenation tests, Mr. Pierluigi Polese for the elemental analyses, and Dr. Paolo Martinuzzi for NMR assistance. We also acknowledge Dr. Antonio Zanotti-Gerosa for helpful discussions on hydrogenation reactions and for giving the opportunity to S.G. to perform hydrogenation tests at Johnson Matthey in Cambridge.

## ■ REFERENCES

(1) (a) Arockiam, P. B.; Bruneau, C.; Dixneuf, P. H. Ruthenium(II)-Catalyzed C−H Bond Activation and Functionalization. *Chem. Rev.* **2012**, *112*, 5879−5918. (b) *Asymmetric Catalysis on Industrial Scale: Challenges, Approaches, and Solutions*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2010; Vol. *1*, p 562. (c) Nolan, S. P.; Clavier, H. Chemoselective Olefin Metathesis Transformations Mediated by Ruthenium Complexes. *Chem. Soc. Rev.* **2010**, *39*, 3305−3316. (d) Beller, M.; Kumar, K., Hydroformylation: Applications in the Synthesis of Pharmaceuticals and Fine Chemicals. In *Transition Metals for Organic Synthesis*, 2nd ed.; Beller, M.; Bolm, C., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vol. *1*, pp 28−55.

(2) Crabtree, R. H. Deactivation in Homogeneous Transition Metal Catalysis: Causes, Avoidance, and Cure. *Chem. Rev.* **2015**, *115*, 127−150.

(3) (a) Xie, X.; Lu, B.; Li, W.; Zhang, Z. Coordination Determined Chemo- and Enantioselectivities in Asymmetric Hydrogenation of Multi-Functionalized Ketones. *Coord. Chem. Rev.* **2018**, *355*, 39−53. (b) Yoshimura, M.; Tanaka, S.; Kitamura, M. Recent Topics in Catalytic Asymmetric Hydrogenation of ketones. *Tetrahedron Lett.* **2014**, *55*, 3635−3640. (c) Shang, G.; Li, W.; Zhang, X., Transition Metal-Catalyzed Homogeneous Asymmetric Hydrogenation. In



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

*Catalytic Asymmetric Synthesis*, 3rd ed.; Ojima, I., Ed.; Wiley: Hoboken, NJ, 2010; Vol. *1*, pp 343−436. (d) *The Handbook of Homogeneous Hydrogenation*. Wiley-VCH: Weinheim, Germany, 2007; Vols. *1*−*3*, p 1568.

(4) (a) Wang, D.; Astruc, D. The Golden Age of Transfer Hydrogenation. *Chem. Rev.* **2015**, *115*, 6621−6686. (b) Foubelo, F.; Nájera, C.; Yus, M. Catalytic Asymmetric Transfer Hydrogenation of Ketones: Recent Advances. *Tetrahedron: Asymmetry* **2015**, *26*, 769−790. (c) Ito, J.-i.; Nishiyama, H. Recent Topics of Transfer Hydrogenation. *Tetrahedron Lett.* **2014**, *55*, 3133−3146. (d) Morris, R. H. Asymmetric Hydrogenation, Transfer Hydrogenation and Hydrosilylation of Ketones Catalyzed by Iron Complexes. *Chem. Soc. Rev.* **2009**, *38*, 2282−2291. (e) Baratta, W.; Rigo, P. 1-(Pyridin-2-yl)methanamine-Based Ruthenium Catalysts for Fast Transfer Hydrogenation of Carbonyl Compounds in 2-Propanol. *Eur. J. Inorg. Chem.* **2008**, *2008*, 4041−4053. (f) Wang, C.; Wu, X.; Xiao, J. Broader, Greener, and More Efficient: Recent Advances in Asymmetric Transfer Hydrogenation. *Chem. - Asian J.* **2008**, *3*, 1750−1770. (g) Samec, J. S. M.; Bäckvall, J.-E.; Andersson, P. G.; Brandt, P. Mechanistic Aspects of Transition Metal-Catalyzed Hydrogen Transfer Reactions. *Chem. Soc. Rev.* **2006**, *35*, 237−248.

(5) Magano, J.; Dunetz, J. R. Large-Scale Carbonyl Reductions in the Pharmaceutical Industry. *Org. Process Res. Dev.* **2012**, *16*, 1156−1184.

(6) (a) Clapham, S. E.; Hadzovic, A.; Morris, R. H. Mechanisms of the $H_2$-Hydrogenation and Transfer Hydrogenation of Polar Bonds Catalyzed by Ruthenium Hydride Complexes. *Coord. Chem. Rev.* **2004**, *248*, 2201−2237. (b) Yamakawa, M.; Ito, H.; Noyori, R. The Metal−Ligand Bifunctional Catalysis: A Theoretical Study on the Ruthenium(II)-Catalyzed Hydrogen Transfer between Alcohols and Carbonyl Compounds. *J. Am. Chem. Soc.* **2000**, *122*, 1466−1478. (c) Petra, D. G. I.; Reek, J. N. H.; Handgraaf, J. W.; Meijer, E. J.; Dierkes, P.; Kamer, P. C. J.; Brussee, J.; Schoemaker, H. E.; van Leeuwen, P. W. N. M. Chiral Induction Effects in Ruthenium(II) Amino Alcohol Catalysed Asymmetric Transfer Hydrogenation of Ketones: An Experimental and Theoretical Approach. *Chem. - Eur. J.* **2000**, *6*, 2818−2829.

(7) Abbreviations: ampy = 2-(aminomethyl)pyridine; en = 1,2-ethylendiamine; bpy = 2,2′-bipyridine; Hamtp = 6-(4-methylphenyl)-2-(aminomethyl)pyridine; amtp = anionic form of 6-(4-methylphenyl)-2-(aminomethyl)pyridine; Hambq = 2-(aminomethyl)benzo[*h*]quinoline; ambq = anionic form of 2-(aminomethyl)benzo[*h*]quinoline; $Hambq^{Ph}$ = 4-phenyl-2-(aminomethyl)benzo[*h*]quinoline; $ambq^{Ph}$ = anionic form of 4-phenyl-2-(aminomethyl)benzo[*h*]quinoline; dppb = 1,4-bis(diphenylphosphine)butane.

(8) (a) Putignano, E.; Bossi, G.; Rigo, P.; Baratta, W. $MCl_2$(ampy)(dppf) (M = Ru, Os): Multitasking Catalysts for Carbonyl Compound/Alcohol Interconversion Reactions. *Organometallics* **2012**, *31*, 1133−1142. (b) Baratta, W.; Chelucci, G.; Herdtweck, E.; Magnolia, S.; Siega, K.; Rigo, P. Highly Diastereoselective Formation of Ruthenium Complexes for Efficient Catalytic Asymmetric Transfer Hydrogenation. *Angew. Chem., Int. Ed.* **2007**, *46*, 7651−7654. (c) Ohkuma, T.; Sandoval, C. A.; Srinivasan, R.; Lin, Q.; Wei, Y.; Muñiz, K.; Noyori, R. Asymmetric Hydrogenation of *tert*-Alkyl Ketones. *J. Am. Chem. Soc.* **2005**, *127*, 8288−8289. (d) Baratta, W.; Herdtweck, E.; Siega, K.; Toniutti, M.; Rigo, P. 2-(Aminomethyl)pyridine-Phosphine Ruthenium(II) Complexes: Novel Highly Active Transfer Hydrogenation Catalysts. *Organometallics* **2005**, *24*, 1660−1669.

(9) (a) Younus, H. A.; Su, W.; Ahmad, N.; Chen, S.; Verpoort, F. Ruthenium Pincer Complexes: Synthesis and Catalytic Applications. *Adv. Synth. Catal.* **2015**, *357*, 283−330. (b) Gunanathan, C.; Milstein, D. Bond Activation and Catalysis by Ruthenium Pincer Complexes. *Chem. Rev.* **2014**, *114*, 12024−12087. (c) Albrecht, M. Cyclometalation Using d-Block Transition Metals: Fundamental Aspects and Recent Trends. *Chem. Rev.* **2010**, *110*, 576−623. (d) Djukic, J. P.; Sortais, J. B.; Barloy, L.; Pfeffer, M. Cycloruthenated Compounds - Synthesis and Applications. *Eur. J. Inorg. Chem.* **2009**, *2009*, 817−853.

(10) (a) Facchetti, S.; Jurcik, V.; Baldino, S.; Giboulot, S.; Nedden, H. G.; Zanotti-Gerosa, A.; Blackaby, A.; Bryan, R.; Boogaard, A.; McLaren, D. B.; Moya, E.; Reynolds, S.; Sandham, K. S.; Martinuzzi, P.; Baratta, W. Preparation of Pincer 4-Functionalized 2-Aminomethylbenzo[*h*]quinoline Ruthenium Catalysts for Ketone Reduction. *Organometallics* **2016**, *35*, 277−287. (b) Baratta, W.; Benedetti, F.; Del Zotto, A.; Fanfoni, L.; Felluga, F.; Magnolia, S.; Putignano, E.; Rigo, P. Chiral Pincer Ruthenium and Osmium Complexes for the Fast and Efficient Hydrogen Transfer Reduction of Ketones. *Organometallics* **2010**, *29*, 3563−3570. (c) Baratta, W.; Siega, K.; Rigo, P. Fast and Chemoselective Transfer Hydrogenation of Aldehydes Catalyzed by a Terdentate CNN Ruthenium Complex [RuCl(CNN)(dppb)]. *Adv. Synth. Catal.* **2007**, *349*, 1633−1636. (d) Baratta, W.; Bosco, M.; Chelucci, G.; Del Zotto, A.; Siega, K.; Toniutti, M.; Zangrando, E.; Rigo, P. Terdentate RuX(CNN)(PP) (X = Cl, H, OR) Complexes: Synthesis, Properties, and Catalytic Activity in Fast Transfer Hydrogenation. *Organometallics* **2006**, *25*, 4611−4620. (e) Baratta, W.; Chelucci, G.; Gladiali, S.; Siega, K.; Toniutti, M.; Zanette, M.; Zangrando, E.; Rigo, P. Ruthenium(II) Terdentate CNN Complexes: Superlative Catalysts for the Hydrogen-Transfer Reduction of Ketones by Reversible Insertion of a Carbonyl Group into the Ru-H Bond. *Angew. Chem., Int. Ed.* **2005**, *44*, 6214−6219.

(11) Baratta, W.; Bossi, G.; Putignano, E.; Rigo, P. Pincer and Diamine Ru and Os Diphosphane Complexes as Efficient Catalysts for the Dehydrogenation of Alcohols to Ketones. *Chem. - Eur. J.* **2011**, *17*, 3474−3481.

(12) Bossi, G.; Putignano, E.; Rigo, P.; Baratta, W. Pincer Ru and Os Complexes as Efficient Catalysts for Racemization and Deuteration of Alcohols. *Dalton Trans.* **2011**, *40*, 8986−8995.

(13) Solinas, M.; Sechi, B.; Baldino, S.; Baratta, W.; Chelucci, G. Hydrogenation of Imines Catalyzed by 2-(Aminomethyl)pyridine-Based Ruthenium and Osmium Complexes. *ChemistrySelect* **2016**, *1*, 2492−2497.

(14) (a) Baratta, W.; Fanfoni, L.; Magnolia, S.; Siega, K.; Rigo, P. Benzo[*h*]quinoline Pincer Ruthenium and Osmium Catalysts for Hydrogenation of Ketones. *Eur. J. Inorg. Chem.* **2010**, *2010*, 1419−1423. (b) Baratta, W.; Ballico, M.; Baldino, S.; Chelucci, G.; Herdtweck, E.; Siega, K.; Magnolia, S.; Rigo, P. New Benzo[*h*]-quinoline-Based Ligands and their Pincer Ru and Os Complexes for Efficient Catalytic Transfer Hydrogenation of Carbonyl Compounds. *Chem. - Eur. J.* **2008**, *14*, 9148−9160.

(15) Chelucci, G.; Baldino, S.; Baratta, W. Ruthenium and Osmium Complexes Containing 2-(aminomethyl)pyridine (Ampy)-based Ligands in Catalysis. *Coord. Chem. Rev.* **2015**, *300*, 29−85.

(16) (a) Baldino, S.; Facchetti, S.; Nedden, H. G.; Zanotti-Gerosa, A.; Baratta, W. Chemoselective Transfer Hydrogenation of Aldehydes with $HCOONH_4$ Catalyzed by RuCl(CNNPh)(PP) Pincer Complexes. *ChemCatChem* **2016**, *8*, 3195−3198. (b) Baldino, S.; Facchetti, S.; Zanotti-Gerosa, A.; Nedden, H. G.; Baratta, W. Transfer Hydrogenation and Hydrogenation of Commercial-Grade Aldehydes to Primary Alcohols Catalyzed by 2-(Aminomethyl)pyridine and Pincer Benzo[*h*]quinoline Ruthenium Complexes. *ChemCatChem* **2016**, *8*, 2279−2288.

(17) Espinet, P.; Albéniz, A. C., 1,2-Insertion and *β*-Elimination. In *Current Methods in Inorganic Chemistry*; Kurosawa, H., Yamamoto, A., Eds.; Elsevier: Amsterdam, 2003; Vol. 3, pp 293−371.

(18) Smith, M. B. *March's Advances Organic Chemistry: Reactions, Mechanisms and Structure*, 7th ed.; Wiley: Hoboken, NJ, 2013; p 1141.

(19) (a) Werner, T.; Koch, J. Sodium Hydride Catalyzed Tishchenko Reaction. *Eur. J. Org. Chem.* **2010**, *2010*, 6904−6907. (b) Ekoue-Kovi, K.; Wolf, C. One-Pot Oxidative Esterification and Amidation of Aldehydes. *Chem. - Eur. J.* **2008**, *14*, 6302−6315.

(20) Geissman, T. A. The Cannizzaro Reaction. In *Organic Reactions*; Denmark, S. E., Ed.; Wiley: Hoboken, NJ, 1944; Vol. *2*, pp 94−113.

(21) (a) Bolton, P. D.; Grellier, M.; Vautravers, N.; Vendier, L.; Sabo-Etienne, S. Access to Ruthenium(0) Carbonyl Complexes via Dehydrogenation of a Tricyclopentylphosphine Ligand and Decarbonylation of Alcohols. *Organometallics* **2008**, *27*, 5088−5093. (b) Baratta, W.; Del Zotto, A.; Esposito, G.; Sechi, A.; Toniutti, M.; Zangrando, E.; Rigo, P. $RuCl_2[(2,6\text{-}Me_2C_6H_3)PPh_2]_2$: A New



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

Precursor for Cyclometalated Ruthenium(II) Complexes. *Organometallics* **2004**, *23*, 6264−6272. (c) Coalter, J. N., III; Huffman, J. C.; Caulton, K. G. Cleavage of H-C($sp^2$) and C($sp^2$)-X Bonds (X = Alkyl, Aryl, OR, $NR_2$): Facile Decarbonylation, Isonitrile Abstraction, or Dehydrogenation of Aldehydes, Esters, Amides, Amines, and Imines by $[RuHCl(PiPr_3)_2]_2$. *Organometallics* **2000**, *19*, 3569−3578.

(22) Omura, S.; Fukuyama, T.; Murakami, Y.; Okamoto, H.; Ryu, I. Hydroruthenation Triggered Catalytic Conversion of Dialdehydes and Keto Aldehydes to Lactones. *Chem. Commun.* **2009**, 6741−6743.

(23) (a) Saudan, L. A.; Saudan, C. M.; Debieux, C.; Wyss, P. Dihydrogen Reduction of Carboxylic Esters to Alcohols under the Catalysis of Homogeneous Ruthenium Complexes: High Efficiency and Unprecedented Chemoselectivity. *Angew. Chem., Int. Ed.* **2007**, *46*, 7473−7476. (b) Wu, X.; Liu, J.; Li, X.; Zanotti-Gerosa, A.; Hancock, F.; Vinci, D.; Ruan, J.; Xiao, J. On Water and in Air: Fast and Highly Chemoselective Transfer Hydrogenation of Aldehydes with Iridium Catalysts. *Angew. Chem., Int. Ed.* **2006**, *45*, 6718−6722. (c) Beck, C. M.; Rathmill, S. E.; Park, Y. J.; Chen, J.; Crabtree, R. H.; Liable-Sands, L. M.; Rheingold, A. L. Aldehyde Decarbonylation Catalysis under Mild Conditions. *Organometallics* **1999**, *18*, 5311−5317.

(24) Miecznikowski, J. R.; Crabtree, R. H. Hydrogen Transfer Reduction of Aldehydes with Alkali-Metal Carbonates and Iridium NHC Complexes. *Organometallics* **2004**, *23*, 629−631.

(25) (a) Cavarzan, D. A.; Fagundes, F. D.; Fuganti, O.; da Silva, C. W. P.; Pinheiro, C. B.; Back, D. F.; Barison, A.; Bogado, A. L.; de Araujo, M. P. Mixed Phosphine/Diimines and/or Amines Ruthenium Carbonyl Complexes: Synthesis, Characterization and Transfer-Hydrogenation. *Polyhedron* **2013**, *62*, 75−82. (b) Prabhu, R. N.; Ramesh, R. Synthesis, Structural Characterization, Electrochemistry and Catalytic Transfer Hydrogenation of Ruthenium(II) Carbonyl Complexes Containing Tridentate Benzoylhydrazone Ligands. *J. Organomet. Chem.* **2012**, *718*, 43−51. (c) Ito, J.-i.; Teshima, T.; Nishiyama, H. Enhancement of Enantioselectivity by Alcohol Additives in Asymmetric Hydrogenation with Bis(oxazolinyl)Phenyl Ruthenium Catalysts. *Chem. Commun.* **2012**, *48*, 1105−1107. (d) Sarmah, B. J.; Dutta, D. K. Chlorocarbonyl Ruthenium(II) Complexes of Tripodal Triphos $\{MeC(CH_2PPh_2)_3\}$: Synthesis, Characterization and Catalytic Applications in Transfer Hydrogenation of Carbonyl Compounds. *J. Organomet. Chem.* **2010**, *695*, 781−785. (e) Zhang, J.; Leitus, G.; Ben-David, Y.; Milstein, D. Efficient Homogeneous Catalytic Hydrogenation of Esters to Alcohols. *Angew. Chem., Int. Ed.* **2006**, *45*, 1113−1115.

(26) (a) Dub, P. A.; Ikariya, T. Catalytic Reductive Transformations of Carboxylic and Carbonic Acid Derivatives Using Molecular Hydrogen. *ACS Catal.* **2012**, *2*, 1718−1741. (b) Fogler, E.; Balaraman, E.; Ben-David, Y.; Leitus, G.; Shimon, L. J. W.; Milstein, D. New CNN-Type Ruthenium Pincer NHC Complexes. Mild, Efficient Catalytic Hydrogenation of Esters. *Organometallics* **2011**, *30*, 3826−3833. (c) Balaraman, E.; Gunanathan, C.; Zhang, J.; Shimon, L. J. W.; Milstein, D. Efficient Hydrogenation of Organic Carbonates, Carbamates and Formates Indicates Alternative Routes to Methanol Based on $CO_2$ and CO. *Nat. Chem.* **2011**, *3*, 609−614.

(27) (a) Muthaiah, S.; Hong, S. H. Acceptorless and Base-Free Dehydrogenation of Alcohols and Amines using Ruthenium-Hydride Complexes. *Adv. Synth. Catal.* **2012**, *354*, 3045−3053. (b) Johnson, T. C.; Morris, D. J.; Wills, M. Hydrogen Generation from Formic Acid and Alcohols Using Homogeneous Catalysts. *Chem. Soc. Rev.* **2010**, *39*, 81−88. (c) Dobereiner, G. E.; Crabtree, R. H. Dehydrogenation as a Substrate-Activating Strategy in Homogeneous Transition-Metal Catalysis. *Chem. Rev.* **2010**, *110*, 681−703. (d) Zhang, J.; Gandelman, M.; Shimon, L. J. W.; Milstein, D. Electron-Rich, Bulky PNN-type Ruthenium Complexes: Synthesis, Characterization and Catalysis of Alcohol Dehydrogenation. *Dalton Trans.* **2007**, 107−113. (e) van Buijtenen, J.; Meuldijk, J.; Vekemans, J. A. J. M.; Hulshof, L. A.; Kooijman, H.; Spek, A. L. Dinuclear Ruthenium Complexes Bearing Dicarboxylate and Phosphine Ligands. Acceptorless Catalytic Dehydrogenation of 1-Phenylethanol. *Organometallics* **2006**, *25*, 873−881.

(28) (a) Figliolia, R.; Baldino, S.; Nedden, H. G.; Zanotti-Gerosa, A.; Baratta, W. Mild N-Alkylation of Amines with Alcohols Catalyzed by the Acetate $Ru(OAc)_2(CO)(DiPPF)$ Complex. *Chem. - Eur. J.* **2017**, *23*, 14416−14419. (b) Watson, A. J. A.; Atkinson, B. N.; Maxwell, A. C.; Williams, J. M. J. Ruthenium-Catalyzed Remote Electronic Activation of Aromatic C-F Bonds. *Adv. Synth. Catal.* **2013**, *355*, 734−740. (c) Zbieg, J. R.; McInturff, E. L.; Krische, M. J. Allenamide Hydro-Hydroxyalkylation: 1,2-Amino Alcohols via Ruthenium-Catalyzed Carbonyl anti-Aminoallylation. *Org. Lett.* **2010**, *12*, 2514−2516. (d) Denichoux, A.; Fukuyama, T.; Doi, T.; Horiguchi, J.; Ryu, I. Synthesis of 2-Hydroxymethyl Ketones by Ruthenium Hydride-Catalyzed Cross-Coupling Reaction of *α,β*-Unsaturated Aldehydes with Primary Alcohols. *Org. Lett.* **2010**, *12*, 1−3. (e) Nixon, T. D.; Whittlesey, M. K.; Williams, J. M. J. Transition Metal Catalysed Reactions of Alcohols Using Borrowing Hydrogen Methodology. *Dalton Trans.* **2009**, 753−762. (f) Burling, S.; Paine, B. M.; Nama, D.; Brown, V. S.; Mahon, M. F.; Prior, T. J.; Pregosin, P. S.; Whittlesey, M. K.; Williams, J. M. J. C-H Activation Reactions of Ruthenium N-Heterocyclic Carbene Complexes: Application in a Catalytic Tandem Reaction Involving C-C Bond Formation from Alcohols. *J. Am. Chem. Soc.* **2007**, *129*, 1987−1995.

(29) (a) Creswell, C. J.; Dobson, A.; Moore, D. S.; Robinson, S. D. Complexes of the Platinum Metals. 17. Molecular Dynamics of the Species $[M(O_2CR)_2(CO)(PPh_3)_2]$ (M = Ruthenium, R = Methyl, Trifluoromethyl, Pentafluoroethyl, Pentafluorophenyl; M = Osmium, R = Methyl, Trifluoromethyl). *Inorg. Chem.* **1979**, *18*, 2055−2059. (b) Dobson, A.; Robinson, S. D. Complexes of the Platinum Metals. 7. Homogeneous Ruthenium and Osmium Catalysts for the Dehydrogenation of Primary and Secondary Alcohols. *Inorg. Chem.* **1977**, *16*, 137−142.

(30) Ito, J.-i.; Sugino, K.; Matsushima, S.; Sakaguchi, H.; Iwata, H.; Ishihara, T.; Nishiyama, H. Synthesis of NHC-Oxazoline Pincer Complexes of Rh and Ru and Their Catalytic Activity for Hydrogenation and Conjugate Reduction. *Organometallics* **2016**, *35*, 1885−1894.

(31) (a) Ramesh, M.; Kumar, M. D.; Jaccob, M.; Therrien, B.; Venkatachalam, G. Cyclometalated Ruthenium(II) Carbonyl Complexes Containing 2-(biphenylazo)phenolate Ligands: Synthesis, Structure, DFT Study and Catalytic Activity Towards Oxidation and Transfer Hydrogenation. *Inorg. Chim. Acta* **2018**, *477*, 40−50. (b) Ramesh, M.; Prabusankar, G.; Venkatachalam, G. Ru(II) Mediated CH Activation of 1-(biphenylazo)naphthol: Synthesis and Catalytic Evaluation for Transfer Hydrogenation of Ketones. *Inorg. Chem. Commun.* **2017**, *79*, 89−94.

(32) Shi, J.; Hu, B.; Chen, X.; Shang, S.; Deng, D.; Sun, Y.; Shi, W.; Yang, X.; Chen, D. Synthesis, Reactivity, and Catalytic Transfer Hydrogenation Activity of Ruthenium Complexes Bearing NNN Tridentate Ligands: Influence of the Secondary Coordination Sphere. *ACS Omega* **2017**, *2*, 3406−3416.

(33) (a) Balaraman, E.; Gnanaprakasam, B.; Shimon, L. J. W.; Milstein, D. Direct Hydrogenation of Amides to Alcohols and Amines under Mild Conditions. *J. Am. Chem. Soc.* **2010**, *132*, 16756−16758. (b) Gunanathan, C.; Ben-David, Y.; Milstein, D. Direct Synthesis of Amides from Alcohols and Amines with Liberation of $H_2$. *Science* **2007**, *317*, 790−792. (c) Zhang, J.; Leitus, G.; Ben-David, Y.; Milstein, D. Facile Conversion of Alcohols into Esters and Dihydrogen Catalyzed by New Ruthenium Complexes. *J. Am. Chem. Soc.* **2005**, *127*, 10840−10841.

(34) Spasyuk, D.; Gusev, D. G. Acceptorless Dehydrogenative Coupling of Ethanol and Hydrogenation of Esters and Imines. *Organometallics* **2012**, *31*, 5239−5242.

(35) Kuriyama, W.; Matsumoto, T.; Ogata, O.; Ino, Y.; Aoki, K.; Tanaka, S.; Ishida, K.; Kobayashi, T.; Sayo, N.; Saito, T. Catalytic Hydrogenation of Esters. Development of an Efficient Catalyst and Processes for Synthesising (*R*)-1,2-Propanediol and 2-(l-Menthoxy)-ethanol. *Org. Process Res. Dev.* **2012**, *16*, 166−171.

(36) (a) Sun, R.; Chu, X.; Zhang, S.; Li, T.; Wang, Z.; Zhu, B. Synthesis, Structure, Reactivity, and Catalytic Activity of Cyclometalated (Phosphine)- and (Phosphinite)ruthenium Complexes.



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

*Eur. J. Inorg. Chem.* **2017**, *2017*, 3174−3183. (b) Baratta, W.; Da Ros, P.; Del Zotto, A.; Sechi, A.; Zangrando, E.; Rigo, P. Cyclometalated Ruthenium(II) Complexes as Highly Active Transfer Hydrogenation Catalysts. *Angew. Chem., Int. Ed.* **2004**, *43*, 3584−3588. (c) Lewis, L. N.; Smith, J. F. Catalytic Carbon-Carbon Bond Formation via ortho-Metalated Complexes. *J. Am. Chem. Soc.* **1986**, *108*, 2728−2735. (d) Lewis, L. N. Enhancement of Catalytic Activity Through Orthometalation. Synthesis, Structure, and Catalytic Activity of a New Orthometalated Ruthenium Complex. *J. Am. Chem. Soc.* **1986**, *108*, 743−749.

(37) Zhang, S.; Baldino, S.; Baratta, W. Synthesis of [RuX(CO)-(dppp)(NN)]Cl (X = H, Cl; NN = en, ampy) Complexes and Their Use as Catalysts for Transfer Hydrogenation. *Organometallics* **2013**, *32*, 5299−5304.

(38) (a) Warner, M. C.; Bäckvall, J.-E. Mechanistic Aspects on Cyclopentadienylruthenium Complexes in Catalytic Racemization of Alcohols. *Acc. Chem. Res.* **2013**, *46*, 2545−2555. (b) Conley, B. L.; Pennington-Boggio, M. K.; Boz, E.; Williams, T. J. Discovery, Applications, and Catalytic Mechanisms of Shvo's Catalyst. *Chem. Rev.* **2010**, *110*, 2294−2312. (c) Ahn, Y.; Ko, S.-B.; Kim, M.-J.; Park, J. Racemization Catalysts for the Dynamic Kinetic Resolution of Alcohols and Amines. *Coord. Chem. Rev.* **2008**, *252*, 647−658.

(39) (a) Warner, M. C.; Casey, C. P.; Bäckvall, J.-E., Shvo's Catalyst in Hydrogen Transfer Reactions. In *Bifunctional Molecular Catalysis*; Ikariya, T., Shibasaki, M., Eds.; Springer-Verlag: Berlin, Heidelberg, 2011; Topics in Organometallic Chemistry Vol. *37*, pp 85−125. (b) Shvo, Y.; Czarkie, D.; Rahamim, Y.; Chodosh, D. F. A New Group of Ruthenium Complexes: Structure and Catalysis. *J. Am. Chem. Soc.* **1986**, *108*, 7400−7402.

(40) (a) Stewart, B.; Nyhlen, J.; Martin-Matute, B.; Backvall, J.-E.; Privalov, T. A Computational Study of the CO Dissociation in Cyclopentadienyl Ruthenium Complexes Relevant to the Racemization of Alcohols. *Dalton Trans.* **2013**, *42*, 927−934. (b) Warner, M. C.; Verho, O.; Bäckvall, J.-E. CO Dissociation Mechanism in Racemization of Alcohols by a Cyclopentadienyl Ruthenium Dicarbonyl Catalyst. *J. Am. Chem. Soc.* **2011**, *133*, 2820−2823. (c) Nyhlén, J.; Privalov, T.; Bäckvall, J.-E. Racemization of Alcohols Catalyzed by $[RuCl(CO)_2(\eta^5$-pentaphenylcyclopentadienyl)]: Mechanistic Insights from Theoretical Modeling. *Chem. - Eur. J.* **2009**, *15*, 5220−5229.

(41) Musa, S.; Fronton, S.; Vaccaro, L.; Gelman, D. Bifunctional Ruthenium(II) PCP Pincer Complexes and Their Catalytic Activity in Acceptorless Dehydrogenative Reactions. *Organometallics* **2013**, *32*, 3069−3073.

(42) (a) Humphries, M. E.; Pecak, W. H.; Hohenboken, S. A.; Alvarado, S. R.; Swenson, D. C.; Domski, G. J. Ruthenium(II) Supported by Phosphine-Functionalized N-heterocyclic Carbene Ligands as Catalysts for the Transfer Hydrogenation of Ketones. *Inorg. Chem. Commun.* **2013**, *37*, 138−143. (b) Deb, B.; Sarmah Podma, P.; Dutta Dipak, K. Synthesis of Dicarbonylruthenium(II) Complexes of Functionalized P,S-Chelating Diphosphane Ligands and Their Catalytic Transfer Hydrogenation. *Eur. J. Inorg. Chem.* **2010**, *2010*, 1710−1716. (c) Deb, B.; Borah, B. J.; Sarmah, B. J.; Das, B.; Dutta, D. K. Dicarbonylruthenium(II) Complexes of Diphosphine Ligands and their Catalytic Activity. *Inorg. Chem. Commun.* **2009**, *12*, 868−871.

(43) Naziruddin, A. R.; Huang, Z.-J.; Lai, W.-C.; Lin, W.-J.; Hwang, W.-S. Ruthenium(II) Carbonyl Complexes Bearing CCC-Pincer bis-(carbene) Ligands: Synthesis, Structures and Activities Toward Recycle Transfer Hydrogenation Reactions. *Dalton Trans.* **2013**, *42*, 13161−13171.

(44) Giboulot, S.; Baldino, S.; Ballico, M.; Nedden, H. G.; Zuccaccia, D.; Baratta, W. Cyclometalated Dicarbonyl Ruthenium Catalysts for Transfer Hydrogenation and Hydrogenation of Carbonyl Compounds. *Organometallics* **2018**, *37*, 2136−2146.

(45) (a) Kobayashi, K.; Tanaka, K. Approach to Multi-Electron Reduction Beyond Two-Electron Reduction of $CO_2$. *Phys. Chem. Chem. Phys.* **2014**, *16*, 2240−2250. (b) Ishida, H.; Tanaka, K.; Morimoto, M.; Tanaka, T. Isolation of Intermediates in the Water Gas Shift Reactions Catalyzed by $[Ru(bpy)_2(CO)Cl]^+$ and $[Ru(bpy)_2(CO)_2]^{2+}$. *Organometallics* **1986**, *5*, 724−730.

(46) (a) Aguirre, P.; López, R.; Villagra, D.; Azocar-Guzman, I.; Pardey, A. J.; Moya, S. A. Synthesis of Ruthenium Complexes with Carbonyl and Polypyridyl Ligands Derived from Dipyrido[3,2-a:2′,3′-c]phenazine: Application to the Water Gas Shift Reaction. *Appl. Organomet. Chem.* **2003**, *17*, 36−41. (b) Luukkanen, S.; Haukka, M.; Kallinen, M.; Pakkanen, T. A. The Low-Temperature Water-Gas Shift Reaction Catalyzed by Sodium-Carbonate-Activated Ruthenium Mono(bipyridine)/$SiO_2$ Complexes. *Catal. Lett.* **2000**, *70*, 123−125. (c) Haukka, M.; Venäläinen, T.; Kallinen, M.; Pakkanen, T. A. Chemically Activated Ruthenium Mono(bipyridine)/$SiO_2$ Catalysts in Water-Gas Shift Reaction. *J. Mol. Catal. A: Chem.* **1998**, *136*, 127−134.

(47) (a) Baratta, W.; Baldino, S.; Giboulot, S.; Zhang, S. Dicarbonyl Ruthenium and Osmium Catalysts. WO2017/134620A1, February 03, 2017. (b) Baratta, W.; Baldino, S.; Giboulot, S. Monocarbonyl Ruthenium and Osmium Catalysts. WO2017/134618A1, August 10, 2017.

(48) Baratta, W.; Chelucci, G.; Magnolia, S.; Siega, K.; Rigo, P. Highly Productive CNN Pincer Ruthenium Catalysts for the Asymmetric Reduction of Alkyl Aryl Ketones. *Chem. - Eur. J.* **2009**, *15*, 726−732.

(49) Black, D. S. C.; Deacon, G. B.; Thomas, N. C. Ruthenium Carbonyl Complexes. I. Synthesis of $[Ru(CO)_2(bidentate)_2]^{2+}$ Complexes. *Aust. J. Chem.* **1982**, *35*, 2445−2453.

(50) Zhang, S.; Baratta, W. Synthesis of Pincer Ruthenium RuCl(CNN)(PP) Catalysts from $[RuCl(\mu$-Cl$)(\eta^6$-*p*-cymene$)]_2$. *Organometallics* **2013**, *32*, 3339−3342.

(51) The hydrochloride salt of $Hambq^{Ph}$ ($HCl{\cdot}Hambq^{Ph}$) is more air stable than the H*CNN* ligand.

(52) (a) Koike, T.; Ikariya, T. Mechanistic Aspects of Formation of Chiral Ruthenium Hydride Complexes from 16-Electron Ruthenium Amide Complexes and Formic Acid: Facile Reversible Decarboxylation and Carboxylation. *Adv. Synth. Catal.* **2004**, *346*, 37−41. (b) Kuznetsov, V. F.; Yap, G. P. A.; Alper, H. Chiral Ruthenium Complexes with P,N-Ligands Derived from (*S*)-Proline. *Organometallics* **2001**, *20*, 1300−1309. (c) Wong, W.-K.; Lai, K.-K.; Tse, M.-S.; Tse, M.-C.; Gao, J.-X.; Wong, W.-T.; Chan, S. Reactivity of $Ru(OAc)_2(Ph_3P)_2$ Toward Chelating Diphosphine Ligands. X-ray Crystal Structures of *fac*-$Ru(OAc)_2(Ph_3P)$(dppm) and *trans*-$Ru(OAc)_2(P_2N_2H_4)$. *Polyhedron* **1994**, *13*, 2751−2762.

(53) Baratta, W.; Ballico, M.; Del Zotto, A.; Herdtweck, E.; Magnolia, S.; Peloso, R.; Siega, K.; Toniutti, M.; Zangrando, E.; Rigo, P. Pincer CNN Ruthenium(II) Complexes with Oxygen-Containing Ligands ($O_2CR$, OAr, OR, $OSiR_3$, $O_3SCF_3$): Synthesis, Structure, and Catalytic Activity in Fast Transfer Hydrogenation. *Organometallics* **2009**, *28*, 4421−4430.

(54) (a) Brammer, L. Metals and Hydrogen Bonds. *Dalton Trans.* **2003**, 3145−3157. (b) Steiner, T. The Hydrogen Bond in the Solid State. *Angew. Chem., Int. Ed.* **2002**, *41*, 48−76. (c) Aullón, G.; Bellamy, D.; Guy Orpen, A.; Brammer, L.; Bruton, E. A. Metal-Bound Chlorine Often Accepts Hydrogen Bonds. *Chem. Commun.* **1998**, 653−654.

(55) Baratta, W.; Ballico, M.; Esposito, G.; Rigo, P. Role of the $NH_2$ Functionality and Solvent in Terdentate CNN Alkoxide Ruthenium Complexes for the Fast Transfer Hydrogenation of Ketones in 2-Propanol. *Chem. - Eur. J.* **2008**, *14*, 5588−5595.

(56) (a) Strohmeier, W.; Holke, K. Selektive Bulkhydrierung von $\alpha,\beta$-Ungesättigten Aldehyden zu Ungesättigten Alkoholen mit Homogenen Ruthenium-Katalysatoren. *J. Organomet. Chem.* **1980**, *193*, C63−C66. (b) Graser, B.; Steigerwald, H. Aktivitäten von Ru-Komplexen in der Homogenen Bulk-$H_2$-Transfer Reaktion. *J. Organomet. Chem.* **1980**, *193*, C67−C70.

(57) (a) Parekh, V.; Ramsden, J. A.; Wills, M. Ether-Tethered Ru(II)/TsDPEN Complexes; Synthesis and Applications to Asymmetric Transfer Hydrogenation. *Catal. Sci. Technol.* **2012**, *2*, 406−414. (b) Matsunaga, H.; Ishizuka, T.; Kunieda, T. Highly Efficient Asymmetric Transfer Hydrogenation of Ketones Catalyzed by Chiral



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX

'Roofed' *cis*-diamine-Ru(II) Complex. *Tetrahedron Lett.* **2005**, *46*, 3645−3648. (c) Palmer, M. J.; Kenny, J. A.; Walsgrove, T.; Kawamoto, A. M.; Wills, M. Asymmetric Transfer Hydrogenation of Ketones Using Amino Alcohol and Monotosylated Diamine Derivatives of Indane. *J. Chem. Soc., Perkin Trans. 1* **2002**, 416−427. (d) Rhyoo, H. Y.; Yoon, Y.-A.; Park, H.-J.; Chung, Y. K. Use of amino amides derived from proline as chiral ligands in the ruthenium(II)-catalyzed transfer hydrogenation reaction of ketones. *Tetrahedron Lett.* **2001**, *42*, 5045−5048. (e) Jiang, Y.; Jiang, Q.; Zhang, X. A New Chiral Bis(oxazolinylmethyl)amine Ligand for Ru-Catalyzed Asymmetric Transfer Hydrogenation of Ketones. *J. Am. Chem. Soc.* **1998**, *120*, 3817−3818.

(58) (a) Slagbrand, T.; Kivijärvi, T.; Adolfsson, H. Bimetallic Catalysis: Asymmetric Transfer Hydrogenation of Sterically Hindered Ketones Catalyzed by Ruthenium and Potassium. *ChemCatChem* **2015**, *7*, 3445−3449. (b) Pannetier, N.; Sortais, J. B.; Issenhuth, J. T.; Laurent, B.; Sirlin, C.; Holuigue, A.; Lefort, L.; Panella, L.; de Vries, J. G.; Pfeffer, M. Cyclometalated Complexes of Ruthenium, Rhodium and Iridium as Catalysts for Transfer Hydrogenation of Ketones and Imines. *Adv. Synth. Catal.* **2011**, *353*, 2844−2852. (c) Jerphagnon, T.; Haak, R.; Berthiol, F.; Gayet, A. J. A.; Ritleng, V.; Holuigue, A.; Pannetier, N.; Pfeffer, M.; Voelklin, A.; Lefort, L.; Verzijl, G.; Tarabiono, C.; Janssen, D. B.; Minnaard, A. J.; Feringa, B. L.; de Vries, J. G. Ruthenacycles and Iridacycles as Catalysts for Asymmetric Transfer Hydrogenation and Racemisation. *Top. Catal.* **2010**, *53*, 1002−1008. (d) Xing, Y.; Chen, J.-S.; Dong, Z.-R.; Li, Y.-Y.; Gao, J.-X. Highly Efficient Chiral PNNP Ligand for Asymmetric Transfer Hydrogenation of Aromatic Ketones in Water. *Tetrahedron Lett.* **2006**, *47*, 4501−4503. (e) Morris, D. J.; Hayes, A. M.; Wills, M. The "Reverse-Tethered" Ruthenium(II) Catalyst for Asymmetric Transfer Hydrogenation: Further Applications. *J. Org. Chem.* **2006**, *71*, 7035−7044. (f) Matharu, D. S.; Morris, D. J.; Clarkson, G. J.; Wills, M. An Outstanding Catalyst for Asymmetric Transfer Hydrogenation in Aqueous Solution and Formic Acid/Triethylamine. *Chem. Commun.* **2006**, 3232−3234. (g) Hayes, A. M.; Morris, D. J.; Clarkson, G. J.; Wills, M. A Class of Ruthenium(II) Catalyst for Asymmetric Transfer Hydrogenations of Ketones. *J. Am. Chem. Soc.* **2005**, *127*, 7318−7319. (h) Nordin, S. J. M.; Roth, P.; Tarnai, T.; Alonso, D. A.; Brandt, P.; Andersson, P. G. Remote Dipole Effects as a Means to Accelerate [Ru(amino alcohol)]-Catalyzed Transfer Hydrogenation of Ketones. *Chem. - Eur. J.* **2001**, *7*, 1431−1436. (i) Alonso, D. A.; Nordin, S. J. M.; Roth, P.; Tarnai, T.; Andersson, P. G.; Thommen, M.; Pittelkow, U. 2-Azanorbornyl Alcohols: Very Efficient Ligands for Ruthenium-Catalyzed Asymmetric Transfer Hydrogenation of Aromatic Ketones. *J. Org. Chem.* **2000**, *65*, 3116−3122. (j) Müller, D.; Umbricht, G.; Weber, B.; Pfaltz, A. $C_2$-Symmetric 4,4′,5,5′-Tetrahydrobi(oxazoles) and 4,4′,5,5′-Tetrahydro-2,2′-methylenebis[oxazoles] as Chiral Ligands for Enantioselective Catalysis: Preliminary Communication. *Helv. Chim. Acta* **1991**, *74*, 232−240.

(59) Wiedner, E. S.; Chambers, M. B.; Pitman, C. L.; Bullock, R. M.; Miller, A. J. M.; Appel, A. M. Thermodynamic Hydricity of Transition Metal Hydrides. *Chem. Rev.* **2016**, *116*, 8655−8692.

(60) (a) Sandoval, C. A.; Ohkuma, T.; Muñiz, K.; Noyori, R. Mechanism of Asymmetric Hydrogenation of Ketones Catalyzed by BINAP/1,2-Diamine-Ruthenium(II) Complexes. *J. Am. Chem. Soc.* **2003**, *125*, 13490−13503. (b) Noyori, R.; Yamakawa, M.; Hashiguchi, S. Metal-Ligand Bifunctional Catalysis: A Nonclassical Mechanism for Asymmetric Hydrogen Transfer between Alcohols and Carbonyl Compounds. *J. Org. Chem.* **2001**, *66*, 7931−7944.

(61) (a) Baratta, W.; Baldino, S.; Calhorda, M. J.; Costa, P. J.; Esposito, G.; Herdtweck, E.; Magnolia, S.; Mealli, C.; Messaoudi, A.; Mason, S. A.; Veiros, L. F. CNN Pincer Ruthenium Catalysts for Hydrogenation and Transfer Hydrogenation of Ketones: Experimental and Computational Studies. *Chem. - Eur. J.* **2014**, *20*, 13603−13617. (b) Baratta, W.; Siega, K.; Rigo, P. Catalytic Transfer Hydrogenation with Terdentate CNN Ruthenium Complexes: The Influence of the Base. *Chem. - Eur. J.* **2007**, *13*, 7479−7486. (c) Abdur-Rashid, K.; Clapham, S. E.; Hadzovic, A.; Harvey, J. N.; Lough, A. J.; Morris, R. H. Mechanism of the Hydrogenation of Ketones Catalyzed by *trans*-Dihydrido(diamine)ruthenium(II) Complexes. *J. Am. Chem. Soc.* **2002**, *124*, 15104−15118. (d) Alonso, D. A.; Brandt, P.; Nordin, S. J. M.; Andersson, P. G. Ru(arene)(amino alcohol)-Catalyzed Transfer Hydrogenation of Ketones: Mechanism and Origin of Enantioselectivity. *J. Am. Chem. Soc.* **1999**, *121*, 9580−9588.

(62) (a) Dub, P. A.; Gordon, J. C. The Mechanism of Enantioselective Ketone Reduction with Noyori and Noyori-Ikariya Bifunctional Catalysts. *Dalton Trans.* **2016**, *45*, 6756−6781. (b) Dub, P. A.; Henson, N. J.; Martin, R. L.; Gordon, J. C. Unravelling the Mechanism of the Asymmetric Hydrogenation of Acetophenone by [$RuX_2$(diphosphine)(1,2-diamine)] Catalysts. *J. Am. Chem. Soc.* **2014**, *136*, 3505−3521.

(63) Beach, N. J.; Dharmasena, U. L.; Drouin, S. D.; Fogg, D. E. Improved Syntheses of Versatile Ruthenium Hydridocarbonyl Catalysts Containing Electron-Rich Ancillary Ligands. *Adv. Synth. Catal.* **2008**, *350*, 773−777.

(64) Relevant NMR data for [RuCl(amtp)($PCy_3$)(CO)]: $^1$H NMR (400.1 MHz, $CDCl_3$, 20 °C) $\delta$ 4.94 (m, $NH_2$), 3.95 (m, $CH_2N$), 3.82 (m, $CH_2N$), 2.97 (m, $NH_2$); $^{13}C\{^1H\}$ NMR (100.1 MHz, $CDCl_3$, 20 °C) $\delta$ 208.5 (d, $^2J$(C,P) = 17.2 Hz; CO), 179.3 (m; CRu), 51.2 (s; $CH_2N$); $^{31}P\{^1H\}$ NMR (162.0 MHz, $CDCl_3$, 20 °C) $\delta$ 57.9.

(65) (a) Poe, A. J. Pendent Group Effects, PGEs, in P-donor Ligands. *New J. Chem.* **2013**, *37*, 2957−2964. (b) Snelders, D. J. M.; van Koten, G.; Klein Gebbink, R. J. M. Steric, Electronic, and Secondary Effects on the Coordination Chemistry of Ionic Phosphine Ligands and the Catalytic Behavior of Their Metal Complexes. *Chem. - Eur. J.* **2011**, *17*, 42−57. (c) Crabtree, R. H. *The Organometallic Chemistry of the Transition Metals*, 5th ed.; Wiley: Hoboken, NJ, 2009; Vol. *1*, p 520. (d) White, D.; Taverner, B. C.; Leach, P. G. L.; Coville, N. J. Quantification of Substituent and Ligand Size by the Use of Solid Angles. *J. Comput. Chem.* **1993**, *14*, 1042−1049. (e) Coville, N. J.; Loonat, M. S.; White, D.; Carlton, L. Steric Measurement of Substituted Cyclopentadiene Ligands and the Synthesis and Proton NMR Spectral Analysis of [($\eta^5$-$C_5H_4R$)Fe(CO)(L)I] Complexes with Variable R. *Organometallics* **1992**, *11*, 1082−1090. (f) Tolman, C. A. Steric Effects of Phosphorus Ligands in Organometallic Chemistry and Homogeneous Catalysis. *Chem. Rev.* **1977**, *77*, 313−348.

(66) Haack, K.-J.; Hashiguchi, S.; Fujii, A.; Ikariya, T.; Noyori, R. The Catalyst Precursor, Catalyst, and Intermediate in the $Ru^{II}$-Promoted Asymmetric Hydrogen Transfer between Alcohols and Ketones. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 285−288.

(67) Anderson, P. A.; Deacon, G. B.; Haarmann, K. H.; Keene, F. R.; Meyer, T. J.; Reitsma, D. A.; Skelton, B. W.; Strouse, G. F.; Thomas, N. C.; Treadway, J. A.; White, A. H. Designed Synthesis of Mononuclear Tris(heteroleptic) Ruthenium Complexes Containing Bidentate Polypyridyl Ligands. *Inorg. Chem.* **1995**, *34*, 6145−6157.

(68) James, B. R.; Markham, L. D.; Hui, B. C.; Rempel, G. L. Synthesis and Catalytic Properties of some Carbonyltriphenylphosphineruthenium(II) Complexes. *J. Chem. Soc., Dalton Trans.* **1973**, 2247−2252.

(69) Spencer, A.; Wilkinson, G. Reactions of $\mu_3$-oxo-Triruthenium Carboxylates with $\pi$-acid Ligands. *J. Chem. Soc., Dalton Trans.* **1974**, 786−792.



DOI: 10.1021/acs.organomet.8b00919
*Organometallics* XXXX, XXX, XXX−XXX