P-Stereogenic monophosphines with the 2-p-terphenylyl and1-pyrenyl substituents. Application to Pd and Ru asymmetric catalysis

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ABSTRACT

tThe synthesis of five optically pure P-stereogenic monophosphines of the type PPhArR (Ar = 2-p-terphenylyl (a), 1-pyrenyl (b); R = OMe, Me, i-Pr) is described. The ligands were fully characterisedand the absolute configurations of PPh(1-pyrenyl)R (3b and 5b; R = OMe and Me respectively) wereconfirmed by X-ray diffraction. The complexation of the monophosphines to Pd and Ru organometal-lic units yielded the neutral complexes [PdCl(3-2-Me-allyl)P] (10–12) and [RuCl2(6-p-cymene)P](16–18). Complete characterisation, including the crystal structure determination of [RuCl2(6-p-cymene)(PMePh(2-p-terphenyl))] (17a) is provided. Neutral palladium complexes appeared as mixturesof two diastereomers in solution according to NMR. The synthesis and characterisation of four cationic[Pd(3-2-Me-allyl)(P)2]PF6(13 and 14) is also described. The application of neutral Pd complexes tocatalytic styrene hydrovinylation afforded moderate conversions, high chemoselectivities (>92%) to 3-phenyl-1-butene and up to 43% ee with precursor 12a. Cationic Pd complexes were tested as catalyticprecursors in allylic substitution of rac-3-acetoxy-1,3-diphenyl-1-propene (rac-I), with the anion ofdimethylmalonate and benzylamine as nucleophiles, obtaining full conversions and up to 80% ee in alkyl-ation and 60% ee in amination with precursor 13a. Finally, ruthenium complexes were used as catalyticprecursors in transfer hydrogenation of acetophenone, with complete conversions after several hoursbut low enantioselectivities

1. INTRODUCTION

IntroductionThe development of new ligands for enantioselective catalysiswith late transition metals has been the main driving force for thesynthesis of new chiral P(III) compounds for the last decades, sincephosphines and derivatives are known to be ideal ligands to someof the most catalytically active metals [1]. It is well known thatno ligand is ever efficient enough for all the substrates in a particu-lar reaction catalysed by a certain metal. Therefore, optimisation byfine-tuning the steric and electronic properties of the ligands is usu-ally carried out. At present, all sources of chirality are intensivelyexplored and hence a plethora of phosphorus ligands containingstereogenic carbon atoms, axes and planes have been described[1,2].

Given the configurational stability of the phosphorus atoms ithas been known for over a century [3] that the P atom itself canbe a stereogenic element, giving rise to the family of P-stereogenic ligands [4]. This type of ligands has a very long history in enantio-selective homogeneous catalysis, which started in the pioneeringworks of Horner [5] and Knowles [6,7] in Rh-catalysed enantiose-lective hydrogenation. More recently, the interest in P-stereogenicligands has been rising steadily thanks to new synthetic method-ologies and applications in catalysis [4,8,9].

We also devoted some effort to this field with the preparation ofseries of mono- and diphosphine ligands, which were used in Pd-catalysed reactions (hydrovinylation [10–13] and allylic alkylation[14]) and in Ru-catalysed (cyclopropanation [15] and hydrogentransfer [15,16]) enantioselective reactions. Although the opticallypure monophosphine ligands were initially obtained by resolutionof the racemic mixtures by means of Pd complexes [10,11], theyhave more recently obtained by methods based on asymmetric syn-thesis due to its superior versatility. Therefore, P-ligands obtainedby the so-called Evans [17] and the Jugé-Stephan [18] methods havebeen reported. In particular, series of ligands prepared by the Jugé-Stephan method with the general structure depicted in Fig. 1 weredescribed [12,14]

The monophosphine ligands, which contained a phenyl, a poly-cyclic aromatic group and a methoxy or an alkyl group were complexed to Pd and Ru organometallic moieties. The obtainedcomplexes shown in the figure were employed to the catalyticreactions mentioned before. Some of the phosphines, in particularthose bearing the 2-biphenylyl group, were found to be competentligands [12,14,16].

In this paper, the extension of these studies with new phos-phines bearing the 2-p-terphenylyl (a) and 1-pyrenyl (b) groups,rarely found in the literature, chosen with the aim of improvingthe performance of the previous generation of ligands is reported.To the best of our knowledge, the only monophosphine reportedto date that contains the unsubstituted 2-p-terphenylyl group isthe racemic phenyl(2-p-terphenylyl)phosphine oxide [19]. Severalachiral hydroxyterphenylylphosphines have been described andsuccessfully used as ligands in Pd-catalysed cross-coupling reac-tions [20–22] and also extremely bulky phosphines containing a2,3,4,5-tetraphenyl moiety have been reported and used in severalPd-catalysed reactions [23,24]. Finally, a few achiral diphosphines,built around the terphenylyl skeleton, are also known [25–28].Regarding the 1-pyrenyl substituent, 1-diphenylphosphinopyrenehas been described [29].

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2. RESULTS AND DISCUSSION

2.1. Ligand synthesis

From our previous studies [12,13,30] and from others [31,32],it is known that standard Jugé-Stephan [18] procedure isvery well suited to prepare P-stereogenic phosphines bearingo-monosubstituted aryl fragments. The introduction of the o-monosubstituted aryl fragment it is carried out via organolithiumsand therefore it is mandatory to have the suitable precursors toprepare such species. In the present case, the most obvious pre-cursors are the corresponding aryl bromides 2-bromo-p-terphenyl(Bra) and 1-bromopyrene (Brb), which can be easily lithiated withn-butyllithium at low temperatures (Scheme 1).

Following a literature precedent [33], the preparation ofBra was carried out by Suzuki-Miyaura coupling betweenp-biphenylylboronic acid and o-bromoiodobenzene, using[Pd2(dba)3]/PPh3as catalytic precursor and aqueous Na2CO3solution as a base. After some optimisation, Bra could be obtainedas a crystalline solid in good yield. Compound Brb was also prepared with a modified literature method [34], based on thedirect bromination of pyrene with NBS in DMF. This method isvery selective towards the monobromination in position 1 and Brbcould be obtained in high yield with enough purity to be employedin the synthesis of the phosphines. With the bromoarene precur-sors in hand, the Jugé-Stephan methodology was followed to haveaccess to the desired ligands (Scheme 2).

The regioselective ring opening of oxazaphospholidine-borane1 was initially attempted preparing the organolithiums Lia and Libin Et2O at −78◦C as in previous reports [12,35]. It was found, how-ever, that the very low solubility of these species, probably dueto the extensive conjugation of the aryl groups employed, led tolow yields of 2 and the recovery of large quantities of unreacted 1.Therefore, Et2O was switched to THF, in which the organolithiumdid not precipitate. With this modification, 1 was completely con-sumed and good yields of 2 could be obtained. The ring opening wasvery clean with organolithium Lib but, in contrast, Lia led to severalbyproducts as judged by31P spectroscopy. Phosphamide-borane 2afeatured a broad singlet at 70.2 ppm and another two peaks werealso present at 133 and 107 ppm. The signal at higher field could beassigned to the product 9, originated by base-promoted eliminationon 1 instead of the expected substitution at the P atom (Scheme 3).

This elimination reaction has been described previously in theliterature [36] when bulky organolithium reagents are employed.In the case described, it also leads to 1,4-diphenylbenzene, whichcould indeed be recovered during the purification of 2a. It wasfound that this compound and the other unidentified one reactedin the subsequent reactions and the formed byproducts could notbe separated from the desired intermediates. Therefore, the opti-misation of the ring-opening step was mandatory. After someexperimentation, it was discovered that by simply carrying out thereaction in more diluted conditions was enough to maximise theformation of the desired phosphamide-borane 2a and minimise thequantities of impurities to an acceptable level.

Following the standard procedure, acid-mediated methanolysisof 2 produced the corresponding phosphinite-boranes 3 in goodyields. Whereas 3a was a dense colourless oil, 3b was a yellow solidthat precipitated as a pure product during the methanolysis step.

Solutions of phosphinite boranes 3 in Et2O were treatedat low temperature with RLi (R = Me, i-Pr and t-Bu) to obtainmonophosphine-boranes 5 and 6. As expected [12] the bulkyt-Bu group could no be introduced according to31P NMR spectroscopy. Depending on the exact reaction conditions, thepeak of the starting phosphinite-boranes 3 (at ı around +110 ppm)and/or multiple peaks indicating decomposition could be detected.The less bulky i-Pr group could be successfully introduced by reac-tion of i-PrLi with 3a but once again starting phosphinite-boraneand/or multiple peaks were observed when 3b was employed.These results are in line with previously published data [12] indi-cating that the

introduction of a conjugated aromatic substituentin the ring-opening step of the Jugé-Stephan method precludes theintroduction of the t-Bu group and sometimes even the i-Pr group.The protected phosphinite and phosphine ligands were air-stableoils (for Ar = 2-p-terphenylyl) or solids (for Ar = 1-pyrenyl), whichwere characterised by the usual techniques. HPLC analysis on a chi-ral column of the crude products showed that they were present asoptically pure (ee > 95%) products. Single crystals, suitable to per-form X-ray diffraction studies, were obtained for 3b and 5b. Themolecular structures for the two compounds are displayed in Fig. 2.

The crystal structures confirmed that the absolute configura-tions of the P atom were R for 3b and S for 5b, as expectedgiven the enantiomer of ephedrine employed to prepare 3 [(1R,2S)-(−)-ephedrine] and the stereochemical course of each ofthe Jugé-Stephan method steps [18]. Distances and angles ofboth borane adducts were similar to other previously reportedphosphine-boranes [12,16,37]. A parameter that allows the eval-uation of the steric hindrance of the ligand is the mean value ofthe three BPC angles. The smaller the value, the higher the sterichindrance of the ligand. In the present case, the values are 112.88for 3b and 113.46 for 5b, meaning that the former is slightly morebulky than the latter. Both values are in the range observed for otherP-stereogenic phosphine-boranes [12,37]. Borane adducts 3, 5 and6 were conveniently deprotected by neat morpholine at room tem-perature [12,37], affording the free phosphinites (4a and 4b) andphosphines (7a, 7b, and 8a) ready for complexation.

2.2. Neutral Pd complexes

Neutral Pd allylic complexes of the type [PdCl(3-(2-Methylallyl)(P)] (10–12), were easily prepared by the standardmethod, consisting of splitting Pd dimer D1 with two equivalentsof the ligands in dichloromethane at room temperature (Scheme 4)[12].

The complexes were obtained as air-stable pale yellow solids.The analysis of the NMR spectra in CDCl3indicated that, asexpected, they were present as mixtures of two diastereomericspecies, because of the presence of one chiral phosphine and theallyl moiety. Accordingly, two sharp singlets were present in the31P NMR spectra and duplication of the allylic peaks was clearlyobservable in the1H NMR spectra. It has to be pointed out that thepresence of the chiral phosphine ruled out the presence of any sym-metry element and hence in principle H and C atoms of the eachdifferent isomer were all different. The proportion of each isomeris indicative of the discrimination ability of the chiral ligand in the neutral complexes. The isomeric ratio was 1:1 for complexes bear-ing the phosphines with the 1-pyrenyl group (10b and 11b) andfor complex 10a. In contrast, it was around 1:2 for complexes 11aand 12a, similarly to complexes with phosphines containing the2-biphenylyl group [12].

2.3. Cationic Pd complexes

Cationic Pd allylic complexes of the type [Pd(3-(2-Methylallyl)(P)2]PF6(13–15), were easily prepared followinga previously reported method [14]. Thus, dimer D1 dissolved indichloromethane was treated with four equivalents of monophos-phine in the presence of excess of ammonium hexafluorophosphate (Scheme 5).

An aqueous final work-up allowed the isolation of the desiredcationic complexes as air-stable solids. In solution they slowlydecomposed to Pd black and other unknown species as31P NMRspectroscopy evidenced. This process was faster for complexes withphosphines containing the 2-p-terphenylyl group (13a and 14a).The complexes are present as single species in solution but the chi-rality of the phosphine makes each phosphine and each half of theallyl group to appear different in the NMR spectra. For that reason,two sharp doublets (JPP= 29–55 Hz) with strong roof effect wereobserved in the31P NMR spectra and four resonances assignable tothe allylic protons could be seen. Two of them, corresponding

to theanti protons, appeared as sharp doublets (JPP= 9–13 Hz) whereasthe remaining two appeared as broad singlets and corresponded to the two syn protons. In contrast to 13 and 14, solutions of complex15a displayed only two peaks in the31P NMR spectrum and sev-eral peaks belonging to the i-Pr and the allylic moieties in the1HNMR spectrum, which could not be assigned. It is possible the bulk-iness of the phosphine 8a precludes the appropriate coordinationof two ligands to stabilise 15a. This complex was not further usedin catalysis.

2.4. Ru complexes

Similarly to the Pd complexes discussed above, neutral Rucomplexes of the type [RuCl2(6-(p-cymene)(P)] (16–18), werepreparedby splitting the well-known Ru dimer D2 with two equiv-alents of the appropriate phosphorus ligand (Scheme 6) [15,38].

The desired complexes were obtained as air-stable red solidsafter recrystallisation. In solution they were conveniently charac-terised by NMR. They featured a singlet in the31P NMR spectra. In1H and13C NMR spectra, the chirality of the phosphine made allthe H and C atoms of the coordinated aryl moiety of the p-cymeneto appear differentiated as well as the two methyl groups of theisopropyl substituent.

Suitable monocrystals to perform X-ray diffraction studies couldbe obtained for 17a. Its ORTEP representation is displayed in Fig. 3.

The complex shows the typical “piano-stool” pseudotetrahedralgeometry around the Ru atom with the p-cymene ring coordi-nated in 6fashion, making the Ru to adopt a distorted octahedralcoordination environment. The structure allows an additional con-firmation of the absolute configuration of the phosphorus atom ofthe phosphine (S, as a free ligand). The geometric parameters ofthe structure are similar to other previously reported [RuCl2(6-p-cymene)(P)] complexes [15,16,39]. As expected, the two Ru-Cldistances are very similar and that the imaginary line defined bythe two Cl atoms is approximately parallel to the line defined bythe substituted carbons of the p-cymene ring. The average dis-tance between Ru and each of the six aromatic carbon atoms ofthe p-cymene ring is 2.218˚A. These distances can be divided in twogroups: the relatively short ones (those involving the three C atomscloser to the phosphine, average distance of 2.203˚A) and the rel-atively long ones (those involving the three C atoms further awayfrom the phosphine, average distance of 2.232˚A).

2.5. Asymmetric hydrovinylation

Catalytic hydrovinylation can be viewed as the heterocodimeri-sation between an activated olefin and ethylene catalysed by atransition metal complex, usually based on Ni or Pd [40,41]. Theinterest in this reaction is steadily increasing, especially regardingthe asymmetric version [41–43]. The model vinyl arene substrateused was styrene with neutral Pd complexes 10–12 as catalyticprecursors (Scheme 7).

The desired hydrovinylation product, 3-phenyl-1-butene, is achiral compound amenable to enantioselection. The Pd catalyticspecies, however, are also active in isomerising it to achiral (E/Z)-3-phenyl-2-butenes. Other typically encountered byproducts in small amounts are those arising from the dimerisation of eitherethylene (1-butene) or styrene (1,3-diphenyl-1-butenes). The mainchallenge of the hydrovinylation reactions is the design of ligandscapable of forming catalytic precursors leading to high chemo- andenantioselectivities of the hydrovinylation product [41]. With Niand Pd systems, the ligand, usually with P as a donor atom, hasto be monodentate due to the particularities of the catalytic cycle[41] a feature that makes more challenging the design of efficientligands.

Previous research carried out with monophosphines PArPhR(Ar = 1-naphthyl, 9-phenanthryl, 2-biphenylyl; R = OMe, Me, i-Pr)led to some selective catalysts towards 3-phenyl-1-butene in

thehydrovinylation of styrene [12,13,30]. In this paper, these resultscan be conveniently compared to those obtained with the catalyticprecursors based on the 2-p-terphenylyl and 1-pyrenyl phosphinespresented here. The results are given in Table 1.

As expected, all neutral allylic complexes are active in catalytichydrovinylation with very different activities depending on thesubstituents at the P atom, as clearly evidenced by the TOF values at6 h. The order of increasing activity is 10a < 11a < 11b < 12a < 11b. Infact, precursor 11b leads to a very fast catalytic system so in orderto avoid extensive isomerisation of 3-phenyl-1-butene the reactiontime had to be shortened (cf. entries 4 and 5). The catalytic systemsare very selective towards the primary - hydrovinylation product,namely 3-phenyl-1-butene, which is higher than 92% at moderateconversions (entries 2 and 6). Regarding the enantioselectivity, onlythe systems containing the 2-p-terphenylyl substituent in the phos-phine lead to some enantioenriched 3-phenyl-1-butene (entries 1,3 and 6). As no secondary interaction can be envisaged with thiskind of ligands, the moderate enantioselectivities obtained can beexplained by pure steric differentiation [12]. In this regard, the lin-earity of the 2-p-terphenylyl group in the monophosphorus ligandsis clearly better to the planarity of the 1-pyrenyl substituent.

The comparison these results with previously published datawith similar phosphines [12,13,30] show that overall the activi-ties are somewhat lower for the phosphines discussed here. Theselectivities are maintained whereas the enantioselectivities of theprecursors with phosphines bearing the 2-p-terphenylyl group arevery similar to those of the precursors with phosphines bearing the2-biphenylyl group [12,30]. These results show that the introduc-tion of an extra phenyl ring at the end of the 2-biphenylyl moietydoes not improve the performance of the ligands, pointing outthat probably it situates in a position too far away from the cat-alytically active Pd centre to have any remarkable effect. The factthat the 1-pyrenyl-containing phosphine ligands generate precur-sors that give to racemic 3-phenyl-1-butene (compared to up tothe 22% ee obtained with the 1-naphthyl-containing phosphines[12]), demonstrates that this substituent is not adequate for theasymmetric hydrovinylation of styrene.

2.6. Pd-catalysed allylic substitution

Allylic substitution reactions can be defined as the substitutionof a leaving group, located in an allylic position, by an incomingnucleophile, catalysed by a catalytic precursor very often basedon Pd. Its asymmetric version has been thoroughly studied andapplied to numerous natural product syntheses [44] and it iscommonly used to test the performance of new bidentate chi-ral ligands [45]. One of the model substrates in this reactions isracemic trans-1,3-diphenyl-2-propen-1-acetate (1,3-diphenylallylacetate), rac-I, and two of the nucleophiles of reference arethe anion derived from dimethyl malonate and benzylamine(Scheme 8).

Cationic Pd complexes (usually prepared in situ) of the type[Pd(3-allyl)(PP)]X (PP = chiral diphosphine, two monodentatephosphines or in general a bidentate ligand) are the usual precursors in this type of transformation. In order to compare [14]the effect of the modification of the phosphine substituents onthe catalytic outcome, the performance of complexes 13 and 14in asymmetric allylic substitutions was explored. The results aregiven in Table 2.

Regardless of the substituents of the phosphine, all the cationiccomplexes were active both in alkylation and amination of rac-I,leading to quantitative conversions to the substituted product after24 h of reaction time. The enantioselectivities were found to be verydependent on the ligand. It can be seen that phosphines containingthe 1-pyrenyl substituent (entries 3, 4, 7 and 8) are clearly not agood choice for allylic substitutions on rac-I, since they give verylow chiral induction in the products. More interesting results areobtained with precursors with phosphines PPh(2-p-terphenylyl)R(entries 1, 2, 5, 6). For both substitution reactions racemic productsare obtained for R = Me (entries 2 and 6) whereas good enantiose-lectivities are achieved for R = OMe (entries 1 and 5). These resultsare slightly better but

follow the same trend than those previouslypublished with 2-biphenylyl containing monophosphines in allylicalkylation [14].

2.7. Ru-hydrogen transfer

In hydrogen transfer reactions, a carbonyl from a ketone isreduced to the parent alcohol by a hydrogen donor, usually analcohol, under Ru or Ir catalysis [46,47]. These reactions areinteresting because they avoid using hydrogen gas or dangerousmetallic hydrides to reduce the ketone. In the asymmetric version [46,48–50], the model substrate is undoubtedly acetophenone,dissolved in isopropanol as hydrogen donor (Scheme 9).

Although they are not the most typically used precursors, com-plexes of the type [RuCl2(6-p-cymene)P] (P = monophosphorusligand) in the presence of a base, are known to be active in hydrogentransfer reactions [15,16,38,51]. Following previous studies withanalogous complexes, the performance of complexes 16–18 wasstudied. The results are given in Table 3.

All catalytic precursors are active in the reaction at reflux ofisopropanol in the present of excess of t-BuOK, after activating thesystem for 15 min in the absence of acetophenone. Full conversionswere obtained in all cases after 24 of reaction time except for 17b(entry 5). Interestingly, the conversions at the same reaction timesare all very similar except for 16b (entry 4), which is considerablyfaster than the rest. This result is in contrast to previously publishedseries of similar ligands, for which phosphines always led to fasterprecursors compared to the parent phosphinites [15]. On the enan-tioselectivities side, very low enantioselectivities were obtained forthe five precursors. In this case, the elongation of the 2-biphenylylsubstituent is very detrimental to enantioselectivity since precur-sor containing the phosphine P(i-Pr)Ph(2-biphenylyl) [15] leads toa 45% ee under the same conditions but precursor containing thephosphine P(i-Pr)Ph(2-p-terphenylyl) leads to only 12% ee (entry3). A possible explanation is that the long 2-p-terphenylyl moietyforces the phosphine to direct the substituents far away from theRu centre as it is observed in the crystal structure of 17a describedabove.

CONCLUSIONS

ConclusionsIn conclusion, the successful preparation of P-stereogenic phos-phines containing a bulky 2-p-terphenylyl or 1-pyrenyl groupby the Jugé-Stephan method has been described. The new lig-ands have been used to prepare and characterise three families oforganometallic complexes: neutral Pd allylic complexes (10–12),cationic Pd allylic complexes (13 and 14) and neutral Ru p-cymenecomplexes (16–18). Neutral Pd complexes have been used incatalytic hydrovinylation of styrene with good chemo- and regiose-lectivity results for all the ligands and a moderate enantioselectivity(43% ee) with 12a. Cationic Pd complexes have been used in cat-alytic allylic substitutions on rac-I, reaching full conversions bothfor alkylations and aminations, with up to 80% ee in allylic alkyl-ation and up to 60% in amination with complex 13a. Finally, Rucomplexes have been used in hydrogen transfer reactions withgood activities but very low enantioselectivities.

The best enantioselectivities have been invariably obtained withligands containing the 2-p-terphenylyl group. In spite of this, thebest enantioselectivities are only marginally better than those withphosphines containing the 2-biphenylyl group and the overall cat-alytic performance of the presented ligands is not significantlybetter than previous results with phosphines with smaller sub-stituents [12,14,15].

4. GENERAL PROCEDURES FOR CATALYTIC RUNS

4.1. Hydrovinylation reactions

Hydrovinylation reactions were carried out in a stainless-steelautoclave fitted with an external jacket connected to an ethanolbath and the temperature controlled using a thermostat to ±0.5◦C.The internal temperature was controlled with a thermocouple. ThePd precursor (0.01 mmol), styrene (1.04 g, 20 mmol) and AgBF4(2.1 mg, 0.011 mmol) were dissolved in 15 mL of dichloromethaneand stirred for 10 min, protected from light. After filtering off theAgCl formed, the solution was quickly placed, by syringe, into theautoclave, which had been purged by successive vacuum/nitrogencycles and thermostated to 25◦C. Ethylene was admitted until apressure of around 15 bar was reached. After the allotted time, theautoclave was slowly depressurised and 10 mL of a 10% aqueousNH4Cl solution was added. The mixture was stirred for 10 min inorder to quench the catalyst. The organic layer was separated, driedwith Na2SO4, filtered through a plug of SiO2and subjected to GCanalysis.

4.2. Allylic substitutions with dimethyl malonate

Under a nitrogen atmosphere, the appropriate Pd precur-sor (0.01 mmol), trans-1,3-diphenyl-2-propen-1-acetate (rac-I,1 mmol), dimethyl malonate (3 mmol), BSA (3 mmol) and KOAc(1 mg) were dissolved, in this precise order, in 4 mL ofdichloromethane. The flask was covered with an aluminium foiland left stirring for the allotted time. In order to quench thereaction, diethyl ether (20 mL) and aqueous 10% ammonium chlo-rides solution (20 mL) were added. After extraction, the organicphase was dried with anhydrous sodium sulfate, filtered and thesolvents removed in vacuo. The crude was analysed by1H NMRin order to estimate the conversion. The crude was dissolved indichloromethane and passed trough a column of silica to removethe metallic impurities. The eluent was removed in vacuo and theresidue was analysed by NMR and HPLC.

4.3. Allylic substitutions with benzylamine

Under a nitrogen atmosphere, the Pd precursor (0.01 mmol),trans-1,3-diphenyl-2-propen-1-acetate (rac-I, 1 mmol) and benzy-lamine (3 mmol) were dissolved, in this precise order, in 4 mL ofdichloromethane. The flask was covered with an aluminium foiland left stirring for the allotted time. In order to quench the reac-tion, diethyl ether (20 mL) and aqueous 10% ammonium chloridesolution (20 mL) were added. After extraction, the organic phasewas dried with anhydrous sodium sulfate, filtered and the solventsremoved in vacuo. The eluent was removed in vacuo and the residuewas analysed by NMR and HPLC.

4.4. Transfer hydrogenation reactions

A 50 mL schlenk flask was charged with the ruthenium precursor(0.02 mmol) and potassium tert-butoxide (11.2 mg, 0.1 mmol) andwas purged with three vacuum/argon cycles. Under a gentle flowof argon, 25 mL of 2-propanol were added and the flask heated toreflux (85◦C) for 15 min. After that time acetophenone (0.468 mL,4.0 mmol) was rapidly added to start the catalytic run. The reactionwas monitored at the allotted times by taking aliquots of around0.1 mL and analysing them by GC.

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Legends to figures

Figure 1. P-stereogenic monophosphines and their derived Pd and Ru complexes.

Scheme 1. Synthesis of Bra, Brb, Lia and Lib.

Scheme 2. Synthesis of the P-stereogenic ligands.

Scheme 3. Reaction of 1 with Lia.

Figure 2. ORTEP representation of the molecular structures of 3b (left) and 5b (right). Hydrogen atoms have been omitted for clarity. Selected distances (Å) and angles (◦) for3b: P1–O1, 1.6005(14); P1–C17, 1.7934(19); P1–C1, 1.8081(19); P1–B1, 1.899(2); C23–O1, 1.443(2); B1–P1–O1, 115.54(10); B1–P1–C17, 110.06(10); B1–P1–C1, 113.04(10).For 5b: P1–C23, 1.804(3); P1–C17, 1.819(2); P1–C1, 1.816(2); P1–B1, 1.930(3); B1–P1–C23, 109.62(13); B1–P1–C17, 115.55(12); B1–P1–C1, 115.22(13).

Scheme 4. Synthesis of complexes 10–12.

Scheme 5. Synthesis of complexes 13–15.

Scheme 6. Synthesis of complexes 16–18.

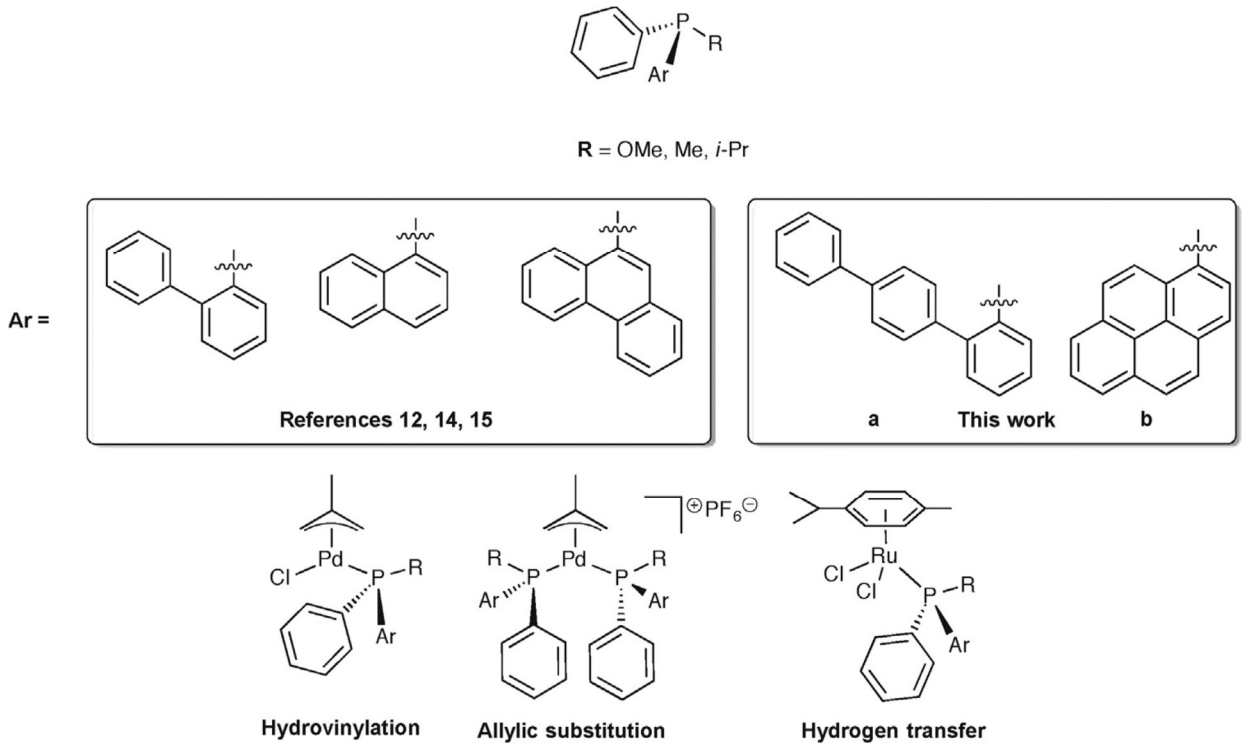
Fig. 3. ORTEP representation of 17a. Thermal ellipsoids drawn at 50% proba-bility level. Hydrogen atoms have been omitted for clarity. Distances (Å) andangles (◦): Ru(1)–Cl(1): 2.4115(8); Ru(1)–Cl(2): 2.4170(8); Ru(1)–P(1): 2.3615(6);P(1)–C(11): 1.818(3); P(1)–C(12): 1.818(3); P(1)–C(18): 1.841(3); C(23)–C(24):1.491(4); C(27)–C(30): 1.487(4); P(1)–Ru(1)–Cl(1): 82.84(3); P(1)–Ru(1)–Cl(2):85.04(3); Cl(1)–Ru(1)–Cl(2): 89.90(3).

Scheme 7. Styrene hydrovinylation

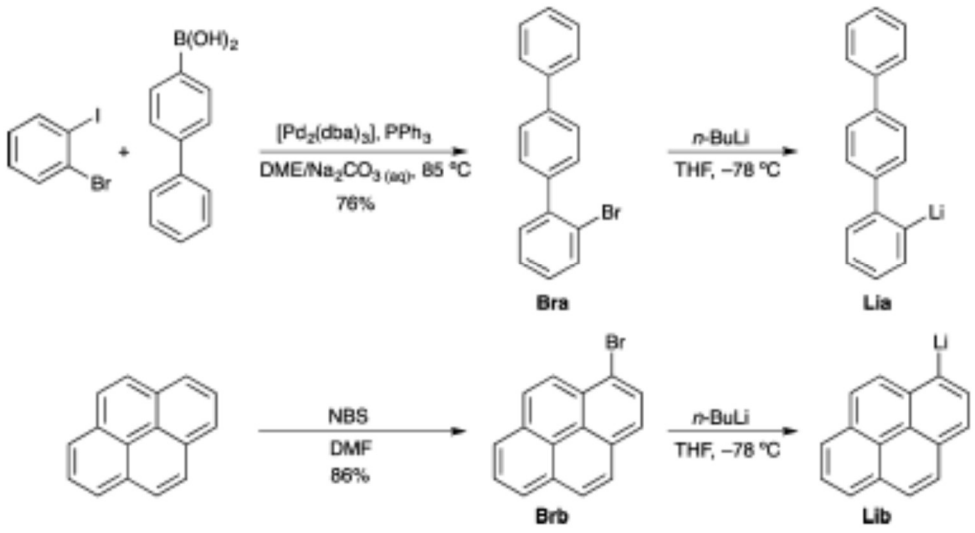
Scheme 8. Allylic substitution reactions on rac-I.

Scheme 9. TH of actophenone.

FIGURE 1


P
R
Ar
R = OMe, Me, i-Pr
Ar =
References 12, 14, 15
a
This work
b
Cl
Pd
P
R
Ar
Hydrovinylation
R
Pd
Ar
PF6
Allylic substitution
Ru
Cl
Hydrogen transfer

SCHEME 1


B(OH)2
I
Br
[Pd2(dba)3], PPh3
DME/Na2CO3 (aq), 85 °C
76%
Br
n-BuLi
THF, −78 °C
Li
Bra
Lia
NBS
DMF
86%
Br
n-BuLi
THF, −78 °C
Li
Brb
Lib

493 **SCHEME 2**

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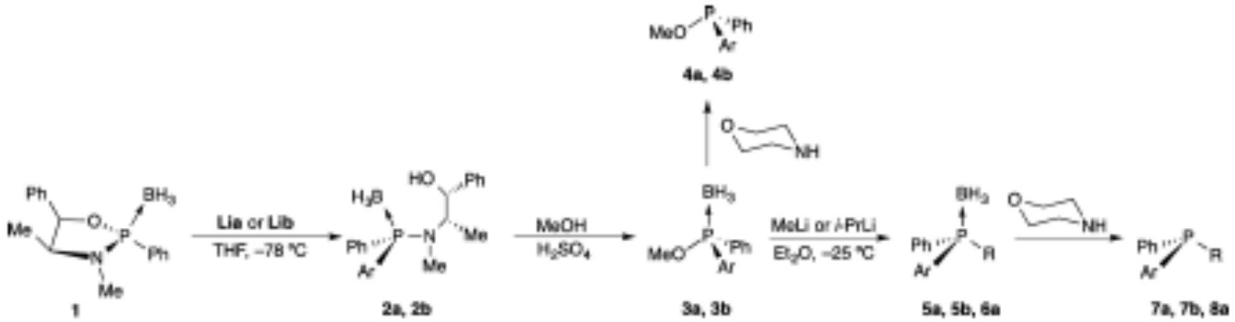

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SCHEME 3

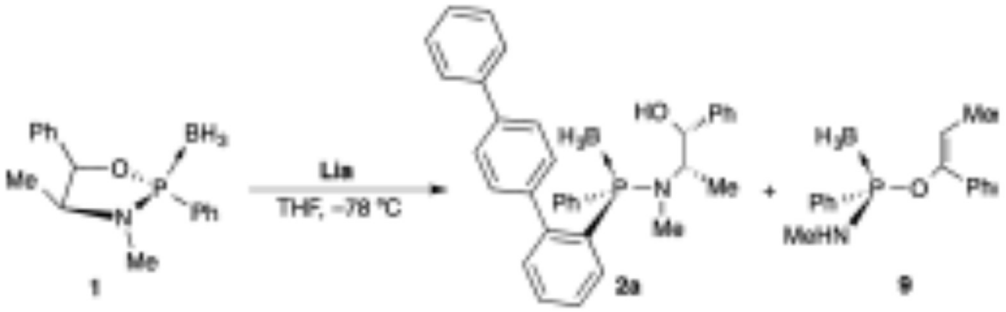
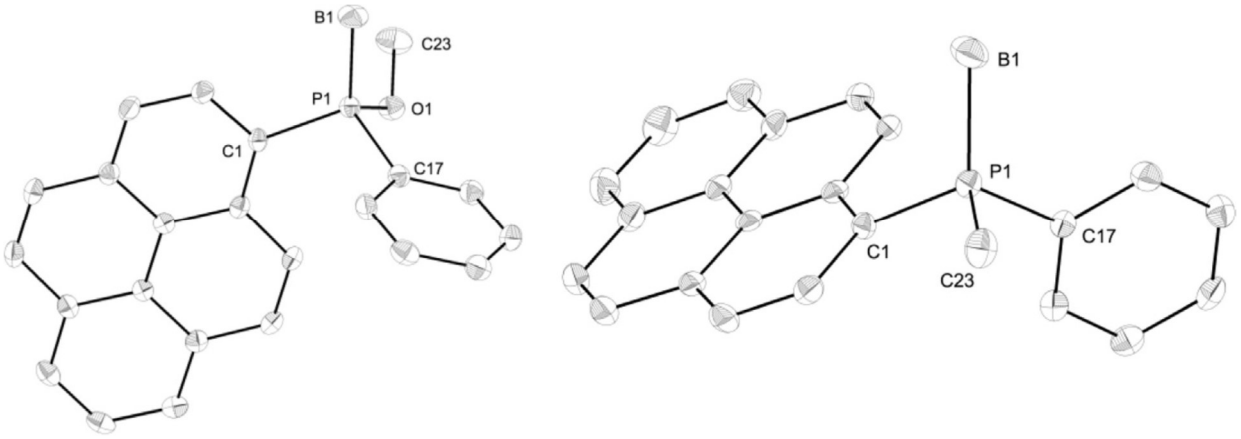
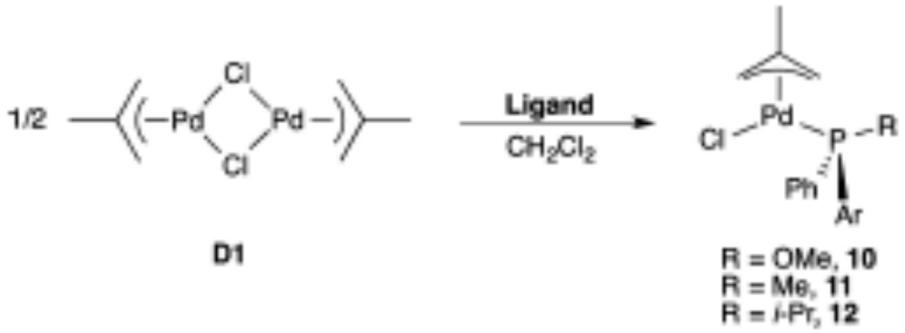

Ph
BH3
Me
O
P
N
Ph
Me
1
LiB
THF, −78 °C
H3B
HO
Ph
Ph
P
N
Me
Me
2a
+
H3B
Me
Ph
P
O
Ph
MeHN
9

FIGURE 2



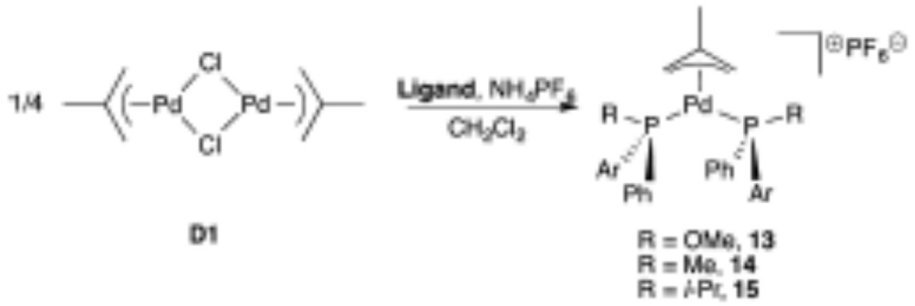
SCHEME 4



D1

R = OMe, **10**
R = Me, **11**
R = *i*-Pr, **12**

SCHEME 5



D1

R = OMe, **13**
R = Me, **14**
R = iPr, **15**

518 **SCHEME 6**

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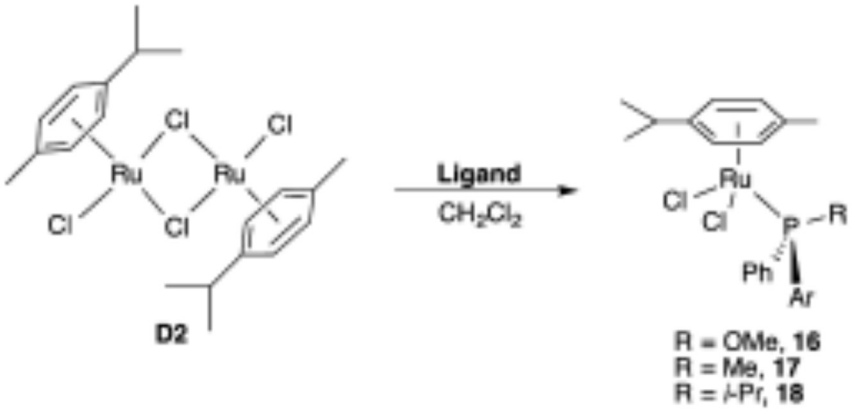

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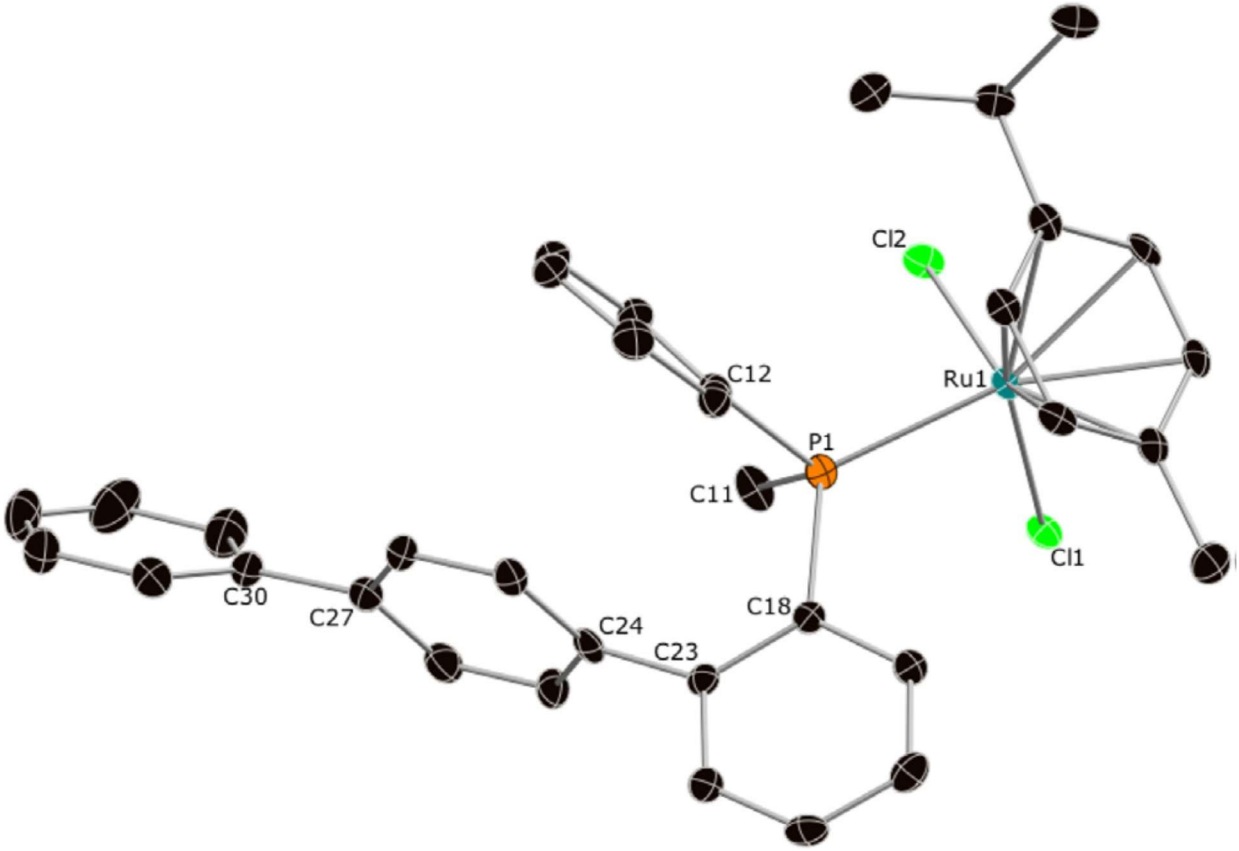
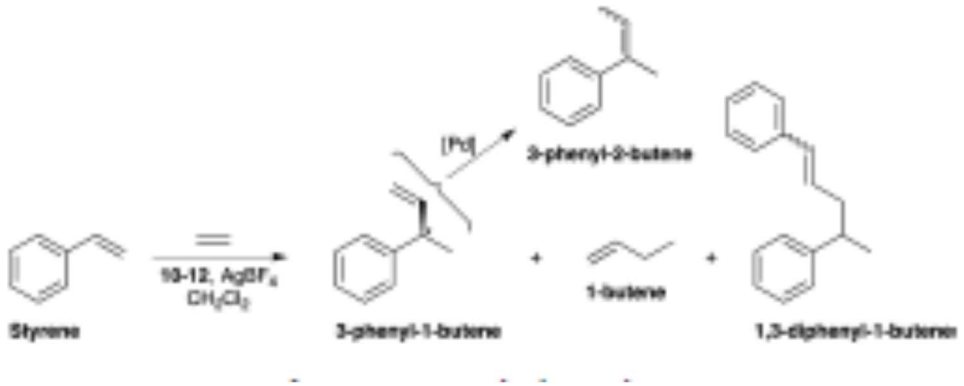
FIGURE 3



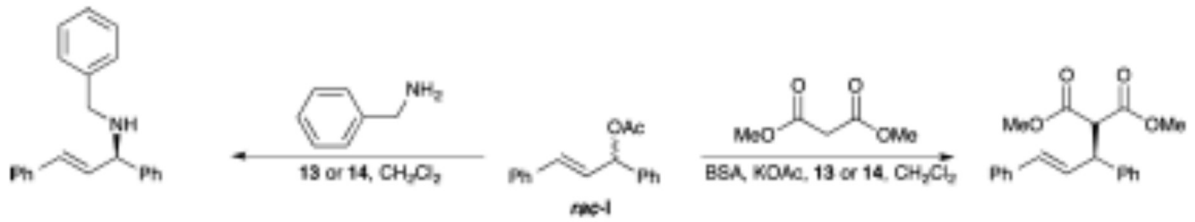
SCHEME 7


[Pd]
3-phenyl-2-butene
10-12, AgBF4
CH2Cl2
Styrene
3-phenyl-1-butene
1-butene
1,3-diphenyl-1-butene

533 **SCHEME 8**

534

535



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SCHEME 9

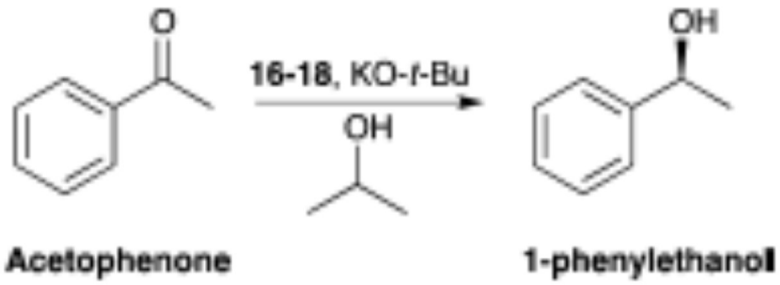

Table 1 Styrene hydrovinylation catalysed with 10–12 complexes.

Entry[a]	Precursor	Time (h)	Conv.[b] (%)	Codimers[c] (%)	Select.[d] (%)	TOF[e] (h^{-1})	ee (%)
1	**10a**	6	9.1	9.1	>99.9	15	34 (R)
2	**10b**	6	43.2	41.9	92.6	68	5 (S)
3	**11a**	6	23.1	22.8	95.0	38	19 (S)
4	**11b**	6	>99.9	97.5	3.7	–	–
5	**11b**	1	16.9	16.9	>99.9	165	3 (S)
6[f]	**12a**	6	62.6	62.6	95.8	106	43 (S)

[a] Catalytic conditions: 25 °C, ~15 bar of initial pressure of ethylene in 15 mL of CH_2Cl_2. Ratio styrene/Pd = 1000/1.
[b] Conversion of starting styrene.
[c] Total amount of codimers.
[d] Percentage of 3-phenyl-1-butene/codimers.
[e] TOF values calculated from the total amount of codimers formed.
[f] This result had already been reported in a review [41].

548 **Table 2** Results of asymmetric allylic substitutions of rac-I with complexes 13 and 14.
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Entry[a]	Nucleophile	Precursor	Conversion (%)[b]	ee (%)[c]
1	DMM	**13a**	>99	80 (S)
2	DMM	**14a**	>99	<5
3	DMM	**13b**	>99	<5
4	DMM	**14b**	>99	7 (S)
5	Benzylamine	**13a**	>99	60 (R)
6	Benzylamine	**14a**	>99	<5
7	Benzylamine	**13b**	>99	<5
8	Benzylamine	**14b**	>99	<5

[a] Catalytic conditions for allylic alkylations with dimethyl malonate: Pd complex (0.01 mmol), **rac-I** (1 mmol), dimethyl malonate (3 mmol), BSA (3 mmol) and KOAc (1 mg) in 4 mL of CH_2Cl_2 at rt for 24 h; for allylic substitutions with benzylamine: Pd complex (0.01 mmol), **rac-I** (1 mmol) and benzylamine (3 mmol) in 4 mL of CH_2Cl_2 at rt for 24 h.

[b] Conversion percentage expressed as **rac-I** consumption, determined by NMR and HPLC.

[c] Enantiomeric excesses determined by HPLC.

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555 **Table 3.** Hydrogen transfer of acetophenone catalysed by complexes 16–18.
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Entry[a]	Precursor	Time (h)	Conversion (%)[b]	ee (%)[c]
1	**16a**	1/3/5/24	9/29/48/99	<5
2	**17a**	1/3/5/24	11/29/41/99	<5
3	**18a**	1/3/5/24	12/29/42/99	12 (R)
4	**16b**	1/3/5/24	43/72/85/99	9 (S)
5	**17b**	1/3/5/24	8/24/39/83	6 (R)

[a] Catalytic conditions: Ru complex (0.02 mmol) and t-BuOK (0.1 mmol) dissolved in 25 mL of i-PrOH and activated at 82 °C during 15 min before adding acetophenone (4.0 mmol).
[b] Conversion of starting acetophenone.
[c] Enantiomeric excess at 24 h.

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