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Modular Synthesis of Novel Chiral Phosphorous Triamides Based on (*S*)-*N*-(Pyrrolidin-2-ylmethyl)aniline and Their Application in Asymmetric Catalysis

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A set of new P-chiral phosphorous triamides (PTAs) based on the (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline backbone was prepared by modular synthetic procedures. The chirality at phosphorus can be controlled to a large extent by the synthetic route, and high diastereomeric purities were achieved for most of the reported ligands. This ligand family was evaluated in the copper-catalysed Michael addition of diethylzinc to cyclohex-2-enone, and moderate enantioselectivities were achieved. In the asymmetric nickel-catalysed hydrovinylation of styrene, good conversions and chemoselectivities, together with promising enantioselectivities of up to 60 %, were obtained with the new PTA ligands even at relatively high reaction temperatures.

Introduction

Phosphorous triamides (PTAs) have been known for a long time as ligands for transition metal complexes.[1] However, in sharp contrast with other ligands formally derived from phosphorous acid,[2–6] very few studies on the synthesis and application of PTAs in asymmetric catalysis have been reported. The first example of their use in transition-metal-catalysed enantioselective transformations was described by Reetz et al.[7] The binaphthyldiazaphospholidine-based PTA **1** (Figure 1) was found to be very sensitive to air and moisture and was isolated as a borane adduct. This ligand gave good activity, but low enantioselectivity in the Rh-catalysed hydroformylation of styrene, whereas no conversion was achieved in the Rh-catalysed hydrogenation of dimethyl itaconate.[7] The introduction of electron-withdrawing substituents at the nitrogens greatly improves the stability of PTAs towards moisture.[8] Gennari and co-workers prepared a variety of ligands of general formula **2** (Figure 1), each containing an electron-poor bis(sulfonyl)-diazaphospholidine moiety.[9] These phosphorous triamide ligands, with different diamine and monoamine backbones, were applied in the Cu-catalysed conjugate addition of diethylzinc to cyclohex-2-enone. Low enantioselectivities were obtained with the majority of the ligands, except with a binaphthyl-based PTA, which led to an enantioselectivity of 75%.[9]

The P-chiral PTA **3** (Figure 1), based on the (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline (**6**, Scheme 1) moiety, was reported previously by Buono and co-workers, who used this compound as an intermediate for the synthesis of phosphorous diamidites[5a,10] and iminoazaphosphorlidine derivatives.[11] This PTA was also used as a derivatising agent for the determination of the enantiomeric purities of chiral alcohols by ^{31}P NMR spectroscopy.[12] This method relies on the facile cleavage of the exocyclic P–N bond by alcohols, resulting in the corresponding diastereomeric phosphorous diamidites and gaseous dimethylamine as the by-product. Only recently have P-chiral PTAs also been considered as ligands and applied in asymmetric catalysis. Schrader′s group used **3** in Cu-catalysed Michael additions of diethylzinc to enones and obtained low enantioselectivities (10–20%).[13] Tsarev et al. reported a variety of ligands based on the (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline moiety, including the PTAs **4** and **5** (Figure 1).[14] In the presence of **5**, low yields (up to 18%) but fairly good enantioselectivities (up to 62%) were achieved in the Pd-catalysed allylic substitution of 1,3-diphenylallyl acetate, whereas **4** gave much lower *ee* values.[14]

Here we report a series of new P-chiral PTAs of the general formula shown in Scheme 1, based on the (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline (**6**) backbone as the common chelating diamine scaffold. Because of the C_1 symmetry of the ligands the phosphorous atom is stereogenic and two different epimers at the P-stereocenter are possible. Steric and electronic tuning of the ligands was accomplished by variation of the monoamine components, including the incorporation of a further two chiral structures in this part.[15] The diastereomeric ratio between the resulting epimers at phosphorus can be controlled to a large extent by use of an

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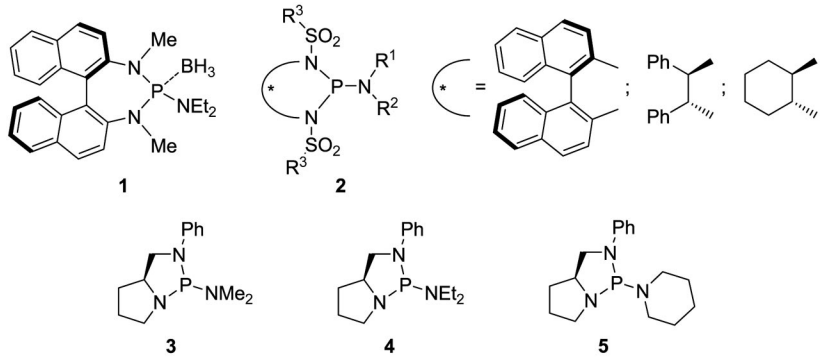
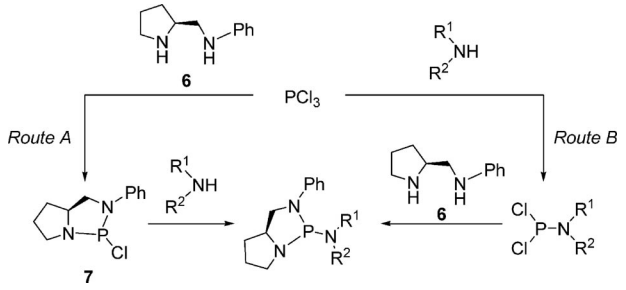


Figure 1. Chiral PTA ligands applied in asymmetric catalysis.

appropriate synthetic route, and high diastereomeric purities have been achieved for most of the described ligands.



Scheme 1. Possible synthetic routes for preparation of PTAs.

This ligand family was evaluated in two benchmark C–C bond-forming reactions. Moderate enantioselectivities were achieved in the copper-catalysed Michael addition of diethylzinc to cyclohex-2-enone. In the more challenging asymmetric nickel-catalysed hydrovinylation of styrene, though, promising enantioselectivities of up to 60% were obtained together with good levels of conversion and chemoselectivity even at relatively high reaction temperatures.

Results and Discussion

Synthesis and Structure

Like other phosphorous[2] or phosphoric acid[16] derivatives, PTAs are in principle accessible by two convergent synthetic routes starting from PCl_3 (Scheme 1).[9] Route A first involves the formation of chlorodiaminophosphane **7**, which is subsequently converted into the desired PTAs by treatment with secondary amines. Alternatively, Route B first entails the synthesis of dichloroaminophosphanes, which are then treated with the diamine **6**. As will be shown in detail, the two synthetic routes are not in all cases equivalent but are instead complementary.

Ligand Synthesis by Route A

The chlorodiaminophosphane **7** was first synthesised by treatment of (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline (**6**) with PCl_3 by a literature procedure.[17] Although the formation of **7** was reported to proceed with complete stereoselection,[17] in our hands compound **7** was repeatedly obtained as a mixture of the two diastereomers **7a** and **7b** (Figure 2) in a ratio of 3.5:1 as indicated by ^{31}P NMR spectroscopy (δ = 153.9 ppm and 145.3 ppm, respectively). Because racemisation of the starting enantiomerically pure diamine under the reaction conditions could be excluded, the two diastereomers must be epimers at the phosphorus. Moreover, the signals of **7a** and **7b** were found to be broad in the ^1H and ^{13}C NMR spectra at room temperature, indicating a rapid equilibrium between the two diastereomers. This was confirmed by EXSY ^{31}P NMR measurements, which clearly show that the two signals at δ = 153.9 ppm and δ = 145.3 ppm are interconverting (Figure 2). Variable-temperature NMR measurements also showed that the signals became sharper at low temperature and broadened at higher temperature but the coalescence temperature could not be reached up to 70 °C in [D_8]toluene. Notably, however, the addition of triethylamine (0.5 equiv.) led to the coalescence of the two signals at room temperature, showing that the presence of a base accelerates the epimerisation process.[18]

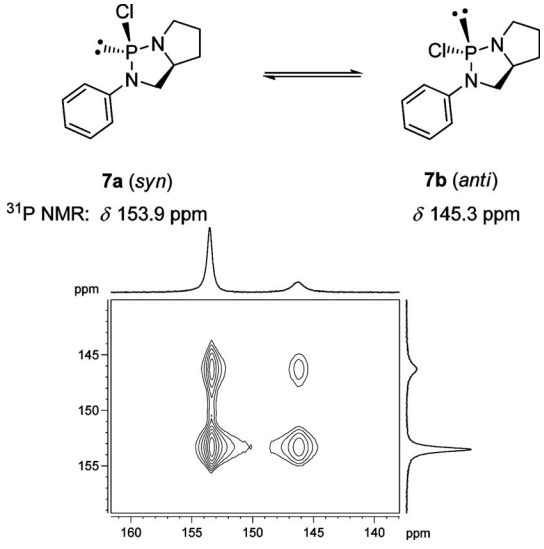


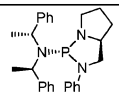
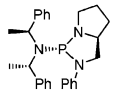
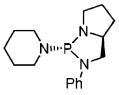
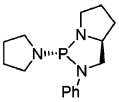
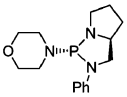
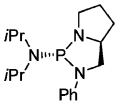
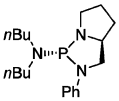
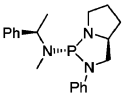
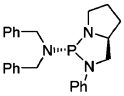
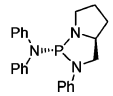
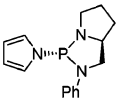
Figure 2. EXSY ^{31}P NMR spectrum of **7**.

The ^{31}P NMR chemical shift reported for **7** in the literature (δ = 153.6 ppm in $CDCl_3$) corresponds to that measured after addition of triethylamine.

The signal at δ = 153.9 ppm in ^{31}P NMR was assigned to the *syn* diastereomer **7a** (absolute configuration S_P) and the signal at δ = 145.3 ppm to the *anti* diastereomer **7b** (absolute configuration R_P) on the basis of the $^2J_{C(1),P}$ value in low-temperature ^{13}C NMR measurements (0 and 22 Hz, respectively).[19] The fact that the *syn* diastereomer is predominant over the *anti* diastereomer is different from the situation with the related phosphorous diamidites and triamides based on (*S*)-pyrrolidin-2-yl-methylamine,[5,10–14] as well as with phosphorous diamidites and phosphoramidites based on (*S*)-prolinol,[20] which were all obtained preferentially as *anti* diastereomers. DFT calculations on **7a** and **7b** [M052X/6–31G(d); IEF-PCM in toluene solution] confirmed, however, that **7a** (*syn*) is more stable than **7b** (*anti*) by 2.2 kcal mol^{-1} in full accordance with the experimental findings.

Treatment of the diastereomeric mixture **7** with various secondary amines afforded ligands **L1**–**L11** with high diastereomeric purities and in good to excellent yields (Table 1). Although the major epimer of the starting chlorodiaminophosphane **7** has a *syn* configuration, all the resulting PTAs are obtained predominantly as *anti* diastereomers, in accordance with related previously reported PTAs.[12,13,17] Ligands **L1**–**L11** show sharp signals in their ^1H, ^{13}C and ^{31}P NMR spectra, and no variation in their

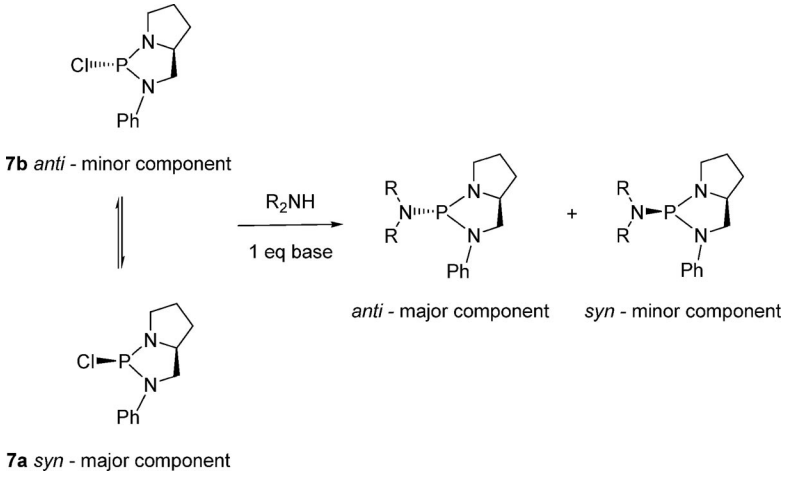
Table 1. Diastereomeric purities of (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline-based PTAs.

Entry	R_2NH	Base (1 equiv.)	Ligand	*d.r.* *anti:syn*	Config. *anti*	Structure *anti*	^{31}P NMR δ (ppm)	Yield [%]
1	(*R*,*R*)-bis(1-phenylethyl)amine	*n*BuLi	**L1**	20:1	*S*,*R*,*R*,S_P[a]		105.8	95
2	(*S*,*S*)-bis(1-phenylethyl)amine	*n*BuLi	**L2**	15:1	*S*,*S*,*S*,S_P		108.8	83
3	piperidine	piperidine	**L3**[b]	45:1	*S*,R_P		114.7	58
4	pyrrolidine	pyrrolidine	**L4**	80:1	*S*,R_P		107.3	59
5	morpholine	morpholine	**L5**	90:1	*S*,R_P		114.5	61
6	diisopropylamine	diisopropylamine	**L6**	>99.9	*S*,S_P[a]		107.0	87
7	dibutylamine	dibutylamine	**L7**	47:1	*S*,R_P		118.2	92
8	(*R*)-(1-phenylethyl)-amine	DMAP	**L8**	115:1	*S*,*R*,R_P[a]		118.5	70
9	dibenzylamine	DMAP	**L9**	68:1	*S*,R_P		118.8	76
10	diphenylamine	BuLi	**L10**	100:1	*S*,R_P		103.2	55
11	pyrrole	BuLi	**L11**	15:1	*S*,S_P		100.8	90

[a] Absolute configuration at the phosphorus confirmed by crystal structure measurement. [b] Ligand **L3** was also reported in reference 14.

relative peak intensities was observed on standing either as solids or in solution, excluding epimerisation processes. Moreover, EXSY ^{31}P NMR measurements of selected ligands showed no exchange, thus confirming configurational rigidity at the phosphorus centres. These observations suggest that dynamic kinetic resolution during the reaction between **7** and the secondary amine is responsible for the observed high diastereoselectivities (Scheme 2). An excess of the secondary amine was used for the preparation of ligands **L3**–**L7**, acting both as building block and hydrochloride scavenger (Table 1, Entries 3–7). Alternative bases were used for less basic or more expensive amine units: DMAP [4-(dimethylamino)pyridine] was chosen as the hydrochloride scavenger for the synthesis of ligands **L8**–**L9** (Table 1, Entries 8–9), whereas deprotonation of the secondary amines with *n*BuLi was employed for the synthesis of ligands **L1**–**L2** and **L10**–**L11** (Table 1, Entries 1–2 and Entries 10–11). The crude products from the synthesis were purified by filtration through a short pad of neutral alumina. This purification method allows the removal of the hydrochloride salt and of unreacted starting amine (if present) in one-step, in most cases yielding the ligands in high purity.

Single crystals suitable for X-ray crystal structure analysis were obtained for the major diastereomers of **L6** and **L8** by crystallisation from C_6D_6 at room temperature. The molecular structures of both ligands are depicted in Figure 3 and each displays the *anti* configuration, corresponding to absolute configurations at phosphorus as S_P for **L6** and R_P for **L8**. The exocyclic P–N^1 bonds are considerably shorter than the P–N bonds within the phosphorus heterocycles and the P–N^3 bonds are again shorter than the P–N^2 bonds. In both structures, the nitrogen atoms N^1 and N^2 are almost planar, whereas the N^3 nitrogens involved in the pyrrolidine rings are slightly pyramidal (sums of all angles: 349.9° and 341.2° for **L6** and **L8**, respectively) and can be considered additional stereocentres, both with *S* configurations. The N^2–P–N^3 angles around phosphorus in the five-membered heterocycles are ca. 90°, leading to significant distortions from tetrahedral arrangements around the chiral P centres. The five-membered ring in **L6** adopts an envelope conformation, whereas in **L8** it is twisted.



Scheme 2. Modular synthesis Route A.

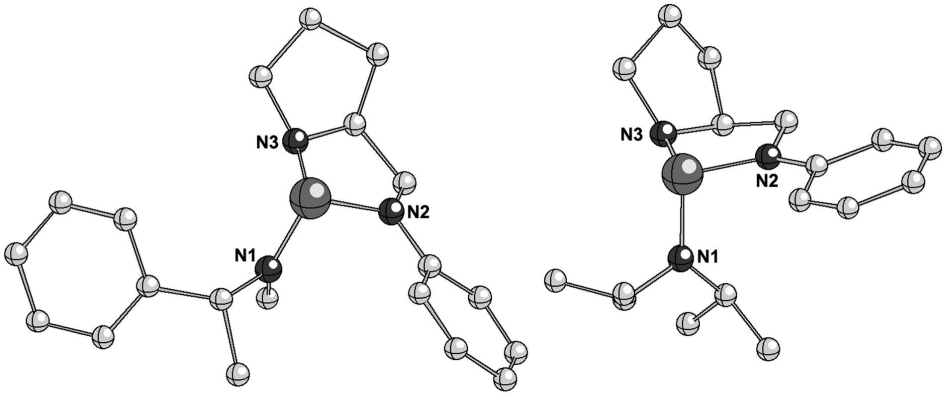


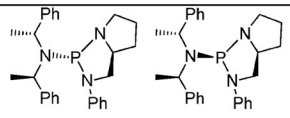
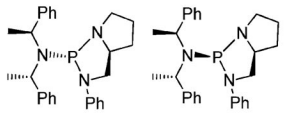
Figure 3. Structures of **L6** (left) and **L8** (right) in the solid state. Hydrogen atoms have been omitted for clarity. Selected atom distances [Å] and angles [°]: **L6**: P–N^1 1.678(1); P–N^2 1.738(1); P–N^3 1.711(1); N^1–P–N^3 108.87°; N^1–P–N^2 100.59°; N^2–P–N^3 90.97°; sums of all angles at nitrogen: N^1 359.17°, N^2 359.21°, N^3 340.46°; **L8**: P–N^1 1.671(1): P–N^2 1.739(1); P–N^3 1.708(1); selected angles: N^1–P–N^3 106.44°; N^1–P–N^2 103.57°; N^2–P–N^3 89.84°; sums of all angles at nitrogen: N^1 359.26°, N^2 355.17°, N^3 341.24°.

Ligand Synthesis by Route B

After demonstrating that Route A is especially suitable for the modular synthesis of ligands **L1**–**L11** with high diastereomeric purity in favour of the *anti* diastereomers, we investigated the alternative Route B, in which the bidentate amine is introduced at the last stage. For this purpose, structures **L1** and **L2** (Table 2), each bearing a chiral bis(1-phenylethyl)amine group, were selected. Firstly, the syntheses of the corresponding dichloroaminophosphane intermediates were carried out by treatment of (*R*,*R*)-bis(1-phenylethyl)amine and its enantiomer with PCl_3.[9] The syntheses of these compounds could be optimised by using DMAP as the base and adjusting the reaction conditions. The desired dichloroaminophosphane intermediates (*R*,*R*)-**8** and (*S*,*S*)-**8** were obtained in excellent yields (95%) in analytically pure forms after extraction with pentane. Subsequently, these precursors were each treated with (*S*)-*N*-phenyl-2-(aminomethyl)pyrrolidine (**6**) in the presence of 2 equiv. of DMAP at room temperature (Scheme 3).

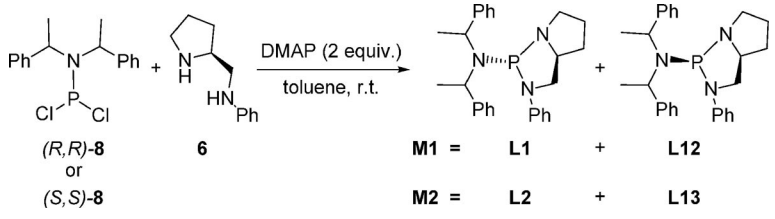
Interestingly, the two synthetic routes were found not to be equivalent in terms of the stereochemical control over the product. In contrast with Route A, in which the *syn* epimers of ligands **L1** and **L2** were barely detectable, these epimers were formed in significant quantities when Route B was applied. In particular, on starting from (*R*,*R*)-**8** a diastereomeric mixture (**M1**) consisting of a 1:1.1 ratio of **L1** and its *syn* diastereomer **L12** was obtained (Table 2, Entry 1). This experimental result could be supported by DFT calculations. Geometry optimizations of **L1** and **L12** showed a negligible difference of 0.02 kcal mol^{-1} [M052X/6–31G(d); gas phase] in the Gibbs free energies, in favour of **L12**. This means in turn that the high diastereoselectivity in favour of **L1** obtained by Route A is the result of kinetic control during the P–N bond formation. With introduction of the bidentate amine in the last step, this differentiation is not effective and both diastereomers are formed according to their relative stabilities. With the dichloroaminophosphane (*S*,*S*)-**8** the diastereomeric mixture **M2** was formed; this even predominantly contains the *syn* diastereomer **L13**, in a 3:1 ratio to **L2** (Table 2, Entry 2).

Table 2. Chemical shifts and compositions of the diastereomeric mixtures **M1** and **M2**.

Diastereomeric mixture	Ligand configuration[a]	^{31}P NMR δ (ppm)	Ratio *anti*:*syn*	Yield [%]
M1	 **L1** (*S*,*R*,*R*,S_P) **L12** (*S*,*R*,*R*,R_P)	**L1** = 105.8: **L12** = 90.2	1 : 1.1	93
M2	 **L2** (*S*,*S*,*S*,S_P) **L13** (*S*,*S*,*S*,R_P)	**L2** = 108.0 **L13** = 86.5	1 : 3	95

[a] The configurations of the ligands are given as follows: firstly the configuration of the pyrrolidine carbon, secondly and thirdly the configurations of the carbons on the chiral secondary amine part, and fourthly the configuration at the phosphorus.

Repeated attempts to isolate the *syn* diastereomer **L12** from the mixture **M1** by crystallisation and column chromatography proved unsuccessful. However, upon conversion of the oily **M1** into the corresponding solid borane adduct **M1**·BH_3, it was possible to isolate the **L1**·BH_3 *anti*



Scheme 3. Synthesis of diastereomeric mixtures **M1** and **M2** by Route B.

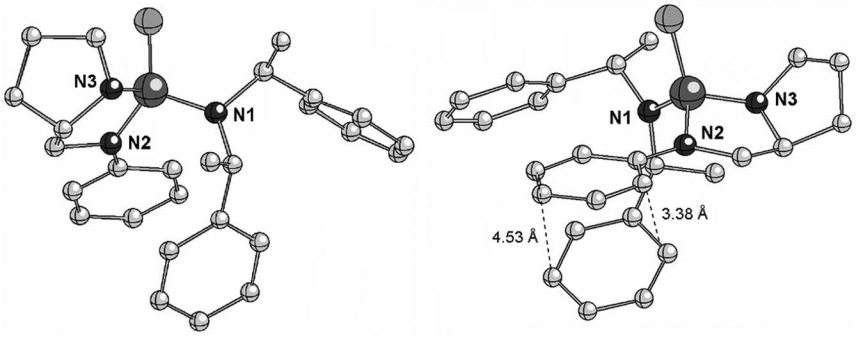


Figure 4. Crystal structure of **L1**·BH_3: front view (left) and rear view (right) showing the proximity of two phenyl rings. Hydrogen atoms have been omitted for clarity. Selected atom distances [Å] and angles [°]: P–B 1.910(6); P–N^1 1.653(4); P–N^2 1.658(4); P–N^3 1.695(4); N^1–P–N^3 111.6(2)°; N^1–P–N^2 110.43(18)°; N^2–P–N^3 92.8(2)° sums of all angles around nitrogen: N^1 358.1°, N^2 356.0°, N^3 349.9.

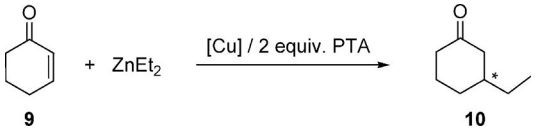
diastereomer in 15% yield by crystallisation. Crystals suitable for X-ray analysis were obtained by slow diffusion of pentane into a $CDCl_3$ solution of the pure **L1**·BH_3 diastereomer and the absolute configuration at the phosphorus was confirmed as S_P (Figure 4).

The crystal structure of **L1**·BH_3 shows features similar to those of **L6** and **L8**: the nitrogen atoms N^1 and N^2 are almost planar (angle sums at the nitrogens: 358.1° and 356°, respectively), whereas N^3 embedded in the pyrrolidine ring is slightly pyramidal (*S* configuration, angle sum 349.9°). The P–N bond lengths increase in the order P–N^1 < P–N^3 < P–N^2 (1.653 Å, 1.658 Å, 1.695 Å, respectively). The N^2–P–N^3 angle in the heterocycle is the smallest at 92.8°, whereas the other two show very similar values: 110.4° for N^1–P–N^2 and 111.6° for N^1–P–N^3. The two methyl groups of the chiral secondary amine moiety point in the same direction. Moreover, the phenyl group of the 1-phenylethylamine and the phenyl group of the diazaphospholidine part are close enough (≈ 4 Å) for a possible extended π–π interaction (Figure 4).[21]

Catalytic Applications

Copper-Catalysed Conjugate Addition

The Cu-catalysed conjugate addition of diethylzinc to cyclohex-2-enone (Scheme 4) is a well-established reaction for monodentate P^{III} ligands, especially for phosphoramidites.[22] Moderate enantioselectivities in a family of electron-poor bis(sulfonyl)diazaphospholidine PTAs were reported by Gennari.[9] As part of a kinetic study, Schrader recently compared the activities of several phosphorous diamidite ligands based on the chiral (pyrrolidin-2-yl)methylamine moiety, including PTA **3**.[13] The catalysts based on the phosphorous diamidites resulted in faster formation of **10** than were achieved with **3**. However, a very low enantioselectivity of 10–20% was obtained in the presence of **3**.

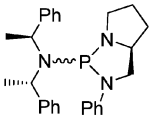
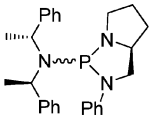
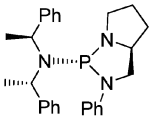
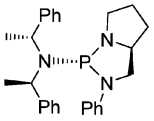
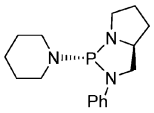
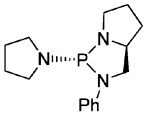
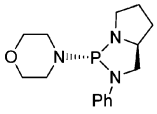
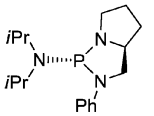
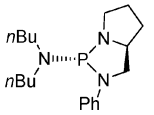
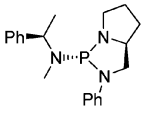
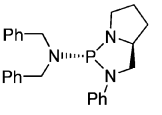
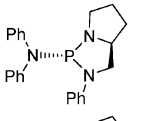
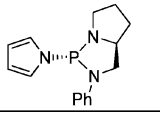


Scheme 4. Michael addition of diethylzinc to cyclohex-2-enone.

For a first evaluation of ligands **L1**–**L12**, we adopted the reaction conditions described by Gennari, with $Cu(OTf)_2$ (5 mol-%) in toluene at –20 °C and a 5 h reaction time.[9] In addition, we also performed the catalytic reactions at a lower temperature (–35 °C) with a longer reaction time (12 h). The results are summarised in Table 3.

Full conversion was obtained with all ligands containing the chiral bis(1-phenylethyl)amine moiety within the indicated times both at –35 °C and –20 °C, and no significant variation in the enantioselectivity was observed in this temperature range (Table 3, Entries 1–4). Interestingly, the diastereomeric mixtures **M1** and **M2** both led to the preferential formation of the *R* product in 23% and 38% *ee*s, respec-

Table 3. Cu-catalysed addition of $ZnEt_2$ to cyclohex-2-enone.[a]

Entry	Ligand	Conv. [%]	*ee* [%]	Conv. [%]	*ee* [%]
		T = –35 °C; *t* = 12 h		*T* = –20 °C; *t* = 5 h	
1	 **M1** (**L1**+**L12**)	99	21 (*R*)	99	23 (*R*)
2	 **M2** (**L2**+**L13**)	99	35 (*R*)	99	38 (*R*)
3	 **L1**	99	15 (*S*)	99	15 (*S*)
4	 **L2**	99	33 (*S*)	99	35 (*S*)
5	 **L3**	48	6 (*S*)	88	21 (*S*)
6	 **L4**	47	8 (*S*)	79	15 (*S*)
7	 **L5**	46	7 (*S*)	–	–
8	 **L6**	93	21 (*S*)	88	20 (*S*)
9	 **L7**	–	–	89	19 (*S*)
10	 **L8**	42	3 (*S*)	92	6 (*S*)
11	 **L9**	96	15 (*S*)	92	24 (*S*)
12	 **L10**	99	50 (*S*)	99	51 (*S*)
13	 **L11**	99	34 (*S*)	88	34 (*S*)

[a] Reaction conditions: toluene, substrate: 0.1 mmol, $Cu(OTf)_2$ 5 mol-%, ligand 10 mol-%.

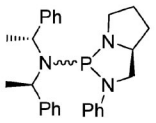
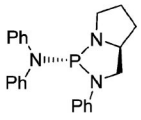
tively (Table 3, Entries 1–2). In contrast, pure **L1** and **L2** (both with *anti* arrangements) led to a product with opposite absolute configuration (*S*) with slightly lower *ee* values (Table 3, Entries 3–4). The switch in the absolute configuration of **10** from *R* to *S* with use of the diastereomerically pure ligands **L1** and **L2** indicates that the chiral information at the donor atom has a major impact on the outcome of the catalysis. Moreover, the slightly higher *ee* values obtained with **M1** and **M2** in relation to those achieved with **L1** and **L2** suggest that the *syn*-configured ligands should represent the "matched" diastereomeric ligands for these transformations. As discussed above, attempts to isolate the pure *syn*-configured diastereomers **L12** and **L13** from **M1** and **M2** (also as their copper complexes) were not successful. The use of excesses of **M1** and **M2** in order to adjust the ratios of **L12**:[Cu] and **L13**:[Cu] precisely to 2:1 did not improve the enantioselectivity.[23]

An enantiomeric excess in a similar range was achieved with ligand **L11**, bearing the sterically much less demanding, achiral pyrrole as secondary amine moiety (Entry 13). Ligands **L3**, **L4** and **L5**, structurally similar to **L11** but containing the more basic piperidine, pyrrolidine and morpholine moieties, turned out to lead to low conversions and enantioselectivities at –35 °C (conv. 46–48%; *ee* 6–8%; Entries 5–7). Notably, ligands **L3** and **L4** gave higher enantioselectivities at –20 °C.[24] Ligands **L6**, **L7** and **L9**, incorporating the acyclic diisopropyl-, di-*n*-butyl- and dibenzylamino moieties, respectively, gave high levels of conversion but modest enantioselectivities (Entries 8, 9 and 11). Very low enantioselectivity was achieved with ligand **L8** bearing (as a monoamine) the chiral (*R*)-(1-phenylethyl) amino structure (Entry 10). The best performance for this ligand class was observed with the (diphenylamino)-substituted ligand **L10**, with a 50% enantiomeric excess at full conversion both at –20 and at –35 °C (Entry 12).

The most promising ligands for this screening were tested further under the conditions introduced by Buono.[25] The results are summarized in Table 4. The diastereomeric mixture **M2** performed significantly better with CuI as the copper precursor and with the catalysis carried out in dichloromethane (Table 3, Entry 1 vs. Table 4, Entry 1). The enantioselectivity could be improved to 60% under these conditions. The use of water as an additive resulted in the formation of racemic **10**, probably because of the high water sensitivity of this ligand. In the case of **L10**, the enantioselectivity could be slightly improved from 50 to 55% under these new conditions and up to 58% *ee* with addition of water (0.5 equiv. with respect to the substrate).

In summary, the *ee* values obtained with the the diastereomeric mixture **M2** and with **L10** are slightly higher than those achieved with the related QUIPHOS ligands under the same conditions[25] and are at the same time among the best values known for PTA ligands.[9] The improvements achieved upon variation of the monoamine part nicely demonstrate the potential of the modular synthetic approach. Although the enantiomeric excesses are, currently, not competitive with those achievable with phosphoramidite ligands, the fact that **L2** probably counteracts the performance of **L13** in **M2** indicates that further activities should be concentrated on the selective synthesis of the *syn* diastereomers as potential lead structures.

Table 4. Cu-catalysed addition of $ZnEt_2$ to cyclohex-2-enone under optimised conditions.[a]

Entry	Ligand		Additive	Conv. [%]	*ee* [%]
1		**M2 (L2+L13)**	–	99	60 (*R*)
2			H_2O	99	*rac*
3		**L10**	–	99	53 (*S*)
4			H_2O	99	58 (*S*)

[a] Reaction conditions: CH_2Cl_2, t = 12 h, T = –20 °C, substrate: 0.1 mmol, 5 mol-% CuI, 10 mol-% ligand.

Catalytic Applications: Nickel-Catalysed Asymmetric Hydrovinylation of Styrene

For many years the state of the art in nickel-catalysed asymmetric hydrovinylation[26] was defined by the azaphospholene ligand developed by Wilke et al. in the early 1980s.[27] In 2002, we showed that phosphoramidites such as Cl-Quinaphos[28] or the Feringa ligand[22b] provide high activity and enantioselectivity in the hydrovinylation of styrenes,[29] and since then numerous examples of synthetically useful applications of related catalytic systems have been reported.[30] Although the Wilke and the Feringa ligands may appear rather different at the first glance, superimpositions of their solid-state structures show important structural similarities.[26] In particular, the ligand regions involved in the coordination to the nickel centre are closely related, both including a (1-phenylethyl)amine moiety and (at least) one P–N bond. These structural analogies and the similar results in catalysis suggest that the two ligands may operate in essentially the same way.[31] Among the ligands reported here, **L8** has the same structural motif, whereas no such unit is present in the related structure **L10**, as shown in Figure 5.

In order to assess the potential of PTAs for the hydrovinylation of styrene the new ligands **L4**, **L8** and **L10** were applied by use of $[Ni(allyl)Br]_2$ as precursor with NaBARF as activator at different temperatures ranging from –50 to 0 °C (Scheme 5). The same catalyst loading of 0.17 mol-% was used in all experiments. The results are summarised in Table 5.

The pyrrolidine-containing ligand **L4** provided good conversion and good chemoselectivity, but low enantioselectivity (Table 5, Entry 1). The diphenyl-substituted ligand **L10** gave the most active catalyst among the tested ligands. It provided 68% conversion within 3 hours at –50 °C with 85% selectivity for **12**, but the asymmetric induction remained low at 33% (Entry 2). At higher temperature the reaction did not stop at the primary product **12**,

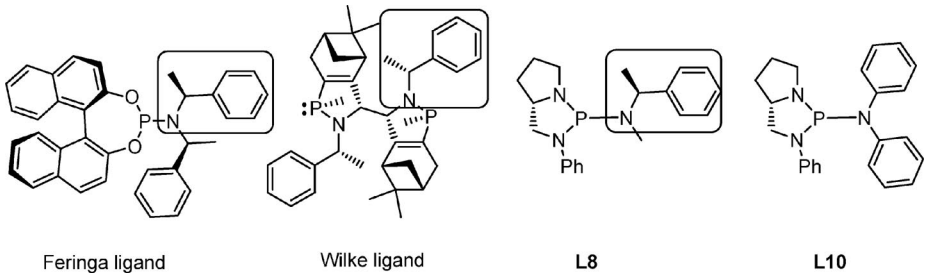
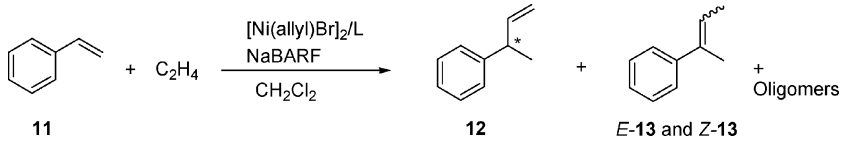
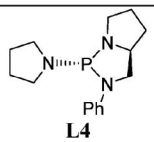
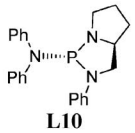
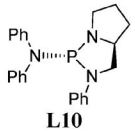
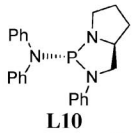
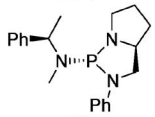
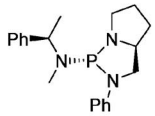


Figure 5. Structural analogies between established ligands for hydrovinylation and some PTAs of this study.



Scheme 5. Nickel-catalysed asymmetric hydrovinylation of styrene.

Table 5. Hydrovinylation of styrene with various PTAs.[a]

Entry	Ligand	T [°C]	t [h]	Conv. [%]	Selectivity [%]			ee 12 [%]
					12	13	oligom.	
1	 L4	–15	3	80	84	5	11	26 (*S*)
2	 L10	–50	3	68	85	13	2	33 (*S*)
3	 L10	–15	2	99	24	65	10	92 (*S*)
4	 L10	0	1	98	2	86	11	99 (*S*)
5	 L8	–15	3	50	86	9	5	60 (*S*)
6	 L8	0	3	98	79	14	7	63 (*S*)

[a] Reaction conditions: CH_2Cl_2, styrene (0.1 mmol), ethylene (1 bar), $[Ni(allyl)Br]_2$ (0.17 mol-%), ligand (0.32 mol-%), NaBARF (0.32 mol-%).

but rapid isomerisation to the thermodynamically more stable **13** occurred. Kinetic resolution of the primary product led to very high *ee*s in the remaining small amounts of **12** (92–99%, Entries 3–4). This subsequent isomerisation coupled with kinetic resolution is a common side reaction in hydrovinylation,[32] but is typically much more pronounced for Pd-based catalysts.[33] In contrast with **L4** and **L10**, the ligand **L8** exhibits a lower reactivity, but considerably higher asymmetric induction in the C–C bond-forming step. At –15 °C, a 60% *ee* was achieved for the *S* isomer, with a chemoselectivity of 86% and only a small degree of isomerisation to **13** (Entry 5). Even at 0 °C, which is a relatively high temperature for selective hydrovinylation, good yields (77%) of **12** and fair enantioselectivities of 63% *ee* could be achieved (Entry 6). This finding is in accordance with the structural similarities of **L8** to other suitable hydrovinylation ligands as outlined in Figure 5.

Conclusions

A set of new phosphorous triamide (PTA) ligands based on (*S*)-pyrrolidin-2-yl-methyl-amine has been prepared through a modular synthetic approach from readily available building blocks. The described PTAs each contain an additional stereocentre at the phosphorus, so each ligand may be formed as mixture of two diastereomers. We have shown that the ratio between the diastereomers can be controlled by using different synthetic routes. By starting from dichloroaminophosphane **7**, high diastereomeric purity in favour of the *anti* diastereomers can be achieved for ligands **L1**–**L11**. In contrast, by coupling the diamine **6** with the dichloro-aminophosphanes (*R*,*R*)-**8** and (*S*,*S*)-**8**, the diastereomeric mixtures **M1** and **M2**, respectively, predominantly containing the *syn* diastereomers, were obtained. Ligands with *anti* stereochemical arrangements were structurally characterised by single-crystal X-ray diffraction.

Moderate enantioselectivities of up to 60% could be achieved in the copper-catalysed conjugate addition of diethylzinc to cyclohex-2-enone. Importantly, the sign of the enantioselectivity is directly related to the absolute configuration at the P atom, and with the diastereomeric mixture

M2 the presence of the *syn* diastereomer led to a higher *ee* with respect to the pure *anti*-**L2**. Among the ligands bearing an achiral monoamine backbone, **L10** turned out to be the best, giving up to 58% *ee* in the same reaction. These results are comparable with those achieved with the best PTA ligands.

Moreover, PTA ligands have been applied for the first time in asymmetric hydrovinylation with promising results. Good yields (77%) and enantioselectivities of up to 63% were achieved with **L8** even at a relatively high reaction temperature of 0 °C. The presence of the 1-phenylethylamine moiety was found to be beneficial for the performance, similar to other P-donor ligands.

This study significantly increases the information on structure and reactivity relating to the so far underrepresented class of PTA ligands. Further directions should concentrate on a selective preparation of the pure *syn* diastereomers and possible applications requiring similar binding properties as in the nickel-catalysed hydrovinylation reaction.

Experimental Section

General Remarks: All reactions involving air-sensitive chemicals were performed under argon by use of standard Schlenk techniques or a glove box.

Reagents *n*BuLi (1 M solution in hexane), CuI, Cu(OTf), Cu(OTf)$_2$, cyclohex-2-enone, ethylbenzene, BH_3 in THF, L-glutamic acid, piperidine, pyrrolidine, diisopropylamine, dibutylamine, dibenzylamine, pyrrole, aniline, diphenylamine and PCl_3 were purchased from Aldrich. 4-(Dimethylamino)pyridine, $LiAlH_4$ and diethylzinc (1 M solution in hexane) were purchased from Fluka.

Reagent Purification Procedures: PCl_3 was heated at reflux for 3 h and distilled under argon. Styrene and ethylbenzene were distilled under reduced pressure and stored in the dark at –30 °C under argon and over molecular sieves. Aniline and triethylamine were distilled under reduced pressure and stored under argon. Liquid amines and cyclohex-2-enone were transferred to a Schlenk flask and stored under argon over molecular sieves. DMAP and dibenzylamine were dried for 1 h in vacuo and stored under argon. The concentration of *n*BuLi was determined by titration with phenanthroline prior to use. For filtration, neutral alumina (Fluka) with Brockman activity 1 was used. It was transferred to a Schlenk flask and dried in vacuo overnight at room temperature. GC analyses were performed on a Sichromat 1–4 gas chromatograph. ^{1}H, ^{13}C and ^{31}P NMR spectra were recorded with Bruker DPX 300 and AV 600 spectrometers. The operating frequencies of these spectrometers for NMR measurements are 300.1 MHz for ^{1}H, 75.5 MHz for ^{13}C and 121.5 MHz for ^{31}P with the DPX 300 spectrometer and 600.1 MHz for ^{1}H, 150.9 MHz for ^{13}C and 242.9 MHz for ^{31}P with the AV 600 spectrometer. For ^{1}H and ^{13}C{^{1}H } NMR spectroscopy, the chemical shifts (δ) are given in ppm with use of the residual solvent signals as internal standards. For ^{31}P NMR spectroscopy the chemical shift values (δ) are given in ppm relative to 85% phosphoric acid as external standard. The multiplicities of the signals were assigned by assuming spectra of first order. The coupling constants (J) are given in Hertz. For the description of the multiplicity of the signals the following symbols are used: s = singlet, d = doublet, t = triplet, q = quadruplet, qi = quintet, m = multiplet, br = broad. Unless otherwise indicated, the spectra were recorded at room temperature. The assignment of the chemical shifts was carried out on the basis of two-dimensional NMR spectra (^{31}P-^{1}H HMBC, ^{1}H-^{1}H COSY, ^{13}C-^{1}H HMBC, ^{13}C-^{1}H HSQC, NOESY). The atom numbering is defined in the chemical as shown and does not comply with nomenclature rules.

^{31}P{^{1}H} EXSY spectra were recorded with a modified NOESY pulse sequence to have ^{1}H broadband decoupling in the phase sensitive mode. A total of 128 scans per FID of 512 or 1 K data points were used per time increment. A total of 128 increments were collected. The EXSY measurements were repeated with a series of mixing times: t_m = 5 μs, 0.5 ms, 2 ms, 10 ms, 50 ms, 100 ms, 200 ms and 300 ms.

High-resolution MS measurements were performed with a Finnigan-MAT 95 spectrometer (EI, 70 eV). The mass of the molecule ion is given.

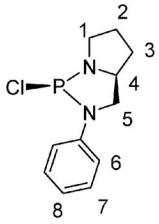
Syntheses

(*S*)-5-Oxopyrrolidine-2-carboxanilide: The synthesis was carried out by a modification of the literature procedure because the originally reported methodology resulted in our hands in scalemic product mixtures.[10] In a round-bottomed flask fitted with a reflux cooler, L-glutamic acid (10.00 g, 67.9 mmol) was suspended in aniline (6.2 mL, 67.9 mmol, 1 equiv.) and the mixture was stirred at 150 °C for three days. The cooler was removed and methanol (100 mL) was added to the hot viscous brown material. The mixture was allowed to cool to room temperature, whereupon the product crystallised from the solution. The crystals were filtered off on a Büchner flask and washed several times with acetone until the filtrate appeared colourless. The product was recrystallised from methanol (100 mL): 9.70 g (70% yield). The spectroscopic data are in agreement with those described in the literature.

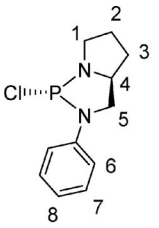
(*S*)-*N*-(Pyrrolidin-2-ylmethyl)aniline (6): The reduction of (*S*)-5-oxopyrrolidine-2-carboxanilide to (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline (**6**) was carried out by the procedure described in the literature.[10] The optical purity of the product was monitored by the following method. (*S*)-*N*-(Pyrrolidin-2-ylmethyl)aniline (10 mg, 0.06 mmol) was introduced by Pasteur pipette into an NMR tube fitted with a screw cap. Subsequently, DMAP (14 mg, 0.12 mmol) and [D$_6$]benzene (0.5 mL) were added and the mixture was agitated for 5 min. Compound (*R*,*R*)-**8** (37.5 mg, 0.06 mmol) was dissolved in [D$_6$]benzene (0.5 mL) and added under argon to the previous solution by syringe. The tube was closed, shaken and allowed to stand at room temperature overnight. The optical purity of the amine was determined by the integration of the ^{31}P NMR signals of the diastereomeric adducts, with the presence of signals at δ = 108.8 ppm and 86.3 ppm indicating *R*-configured amine impurity {*d.r*: [(*S*,*R*,*R*,*Rp*) + (*S*,*R*,*R*,*Sp*)/(*R*,*R*,*R*,*Sp*) + (*R*,*R*,*R*,*Rp*)]}. ^{31}P{^{1}H} NMR: δ = 108.8 (*R*,*R*,*R*,*Sp*), 105.8 (*S*,*R*,*R*,*Rp*), 90.2 (*S*,*R*,*R*,*Sp*), 86.3 (*R*,*R*,*R*,*Rp*) ppm.

(3a*S*)-1-Chloro-2-phenyl-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphole (7): The synthesis was carried out from (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline by the procedure described in the literature.[17]

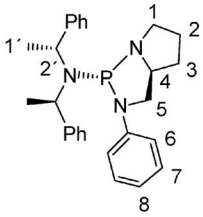
^{1}H NMR ($CDCl_3$): δ = 1.62–1.82 (br, 1 H, 3-H), 2.00–2.08 (m, 1 H, 2-H), 2.09–2.15 (m, 1 H, 2-H), 2.16–2.33 (br, 1 H, 3-H), 3.17–3.33 (br, 1 H, 1-H), 3.46–3.61 (m, 2 H, 5-H), 3.77–3.88 (br, 1 H, 1-H), 4.10–4.19 (m, 1 H, 4-H), 7.02 (t, $^3J_{H8,H7}$ = 7.8 Hz, 1 H, 8-H), 7.11 (d, $^3J_{H6,H7}$ = 8.3 Hz, 2 H, 6-H), 7.32 (dd, $^3J_{H7,H6}$ = 8.3, $^3J_{H7,H8}$ = 7.8 Hz, 2 H, 7-H) ppm. ^{13}C NMR ($CDCl_3$, T = 298 K): δ = 27.8 (br, C-2), 31.3 (br, C-3), 44.4 (br, C-1), 52.6 (br, C-5), 66.5 (br, C-4), 117.6 (br, C-6), 121.8 (br, C-8), 129.3 (s, C-7), 143.0 (d, $^3J_{C,P}$ =



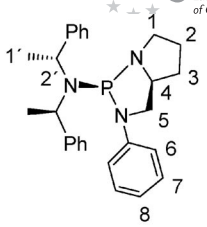
7a



7b



L1: *S,R,R,S*$_p$



L12: *S,R,R,R*$_p$

13 Hz, C_q) ppm. ^{13}C NMR ($CDCl_3$, T = 233 K): δ = 26.9 (C-2b), 28.2 (C-2a), 30.2 (C-3b), 31.4 (C-3a), 44.0 (C-1a), 44.9 (d, $J_{C,P}$ = 22 Hz, C-1b), 51.4 (C-5b), 52.4 (C-5a), 64.9 (C-4b), 66.6 (d, $J_{C,P}$ = 9 Hz, C-4a), 115.6 (d, $J_{C,P}$ = 14 Hz, C-6b), 117.2 (d, $J_{C,P}$ = 14 Hz, C-6a), 120.8 (C-8b), 121.7 (C-8a), 129.3 (C-7a and C-7b), 142.5 (d, $J_{C,P}$ = 11 Hz, C_q-a and C_q-b) ppm. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ = 153.9 (a) and 146.2 (b) , ratio 3.5:1 ppm.

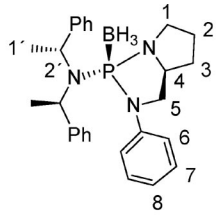
(*R*,*R*)-Bis(1-phenylethyl)phosphoramidous Dichloride [(*R*,*R*)-8]: The synthesis was carried out by a modification of a literature procedure.[9] (*R*,*R*)-Bis(1-phenylethyl)amine (1 g, 4.4 mmol) and DMAP (0.6 g, 4.9 mmol) were dissolved in dry toluene (3 mL). The mixture was stirred for 10 min and cooled down to 0 °C, and subsequently neat PCl_3 (2.3 mL, 3 g, 22 mmol) was introduced by syringe with vigorous stirring. Formation of a colourless precipitate was observed immediately. The mixture was heated to 70 °C overnight, and the solvent and excess of PCl_3 were then removed in vacuo. Pentane (15 mL) was added to the solid residue, and the suspension was vigorously stirred for 30 min, followed by a filtration through dried celite. The extraction and filtration procedure was repeated three times with pentane (10 mL). After removal of the solvent, the product was obtained as a transparent viscous oil, which is sensitive towards air and moisture: 1.37 g (95% yield). The compound can be stored under argon at –30 °C for several months. The spectroscopic data are in agreement with those reported in the literature.[9]

(*R*,*R*)-Bis(1-phenylethyl)phosphoramidous Dichloride [(*S*,*S*)-8]: The same procedure was applied as for the preparation of (*R*,*R*)-**8**. (*S*,*S*)-Bis(1-phenylethyl)amine was used instead of (*R*,*R*)-bis(1-phenylethyl)amine. The spectroscopic data are in agreement with those reported in the literature.[9]

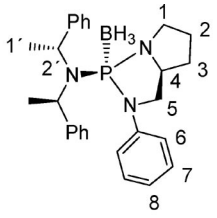
Diastereomeric Mixture M1 (Containing L1 and L12): DMAP (0.757 g, 6.2 mmol) and (*S*)-*N*-(pyrrolidin-2-ylmethyl)aniline (0.537 g, 3.1 mmol) were introduced into a Schlenk flask. Toluene (5 mL) was added and the solution was vigorously stirred for 10 min. Compound (*R*,*R*)-**2** (1 g, 3.1 mmol) was dissolved in toluene (3 mL) and this solution was added dropwise, leading to immediate formation of a colourless precipitate. The reaction mixture was stirred at room temperature overnight and then filtered through a short pad of alumina (ca. 4 cm, Ø = 3 cm), which was washed three times with toluene (15 mL). After removal of the solvent in vacuo, the product was obtained as a transparent viscous oil, which is sensitive towards air and moisture, but can be stored in cold conditions under inert atmosphere for several months: 1.223 g, (93% yield).

^{13}C NMR (C_6D_6): δ = 21.4 (C-1′b), 21.7 (d, $^3J_{C,P}$ = 6 Hz, C-1′a), 25.9 (C-2a), 28.3 (C-2b), 29.5 (C-3b), 32.8 (C-3a), 42.2 (d, $^2J_{C,P}$ = 18 Hz, C-5b), 49.7 (d, $^2J_{C,P}$ = 42 Hz, C-1a), 49.9 (d, $^2J_{C,P}$ = 5 Hz, C-1b), 54.0 (d, $^2J_{C,P}$ = 9 Hz, C-2′a), 54.2 (d, $^2J_{C,P}$ = 10 Hz, C-5a), 62.5 (d, $^2J_{C,P}$ = 8 Hz, C-4a), 63.7 (d, $^2J_{C,P}$ = 6 Hz, C-4b), 115.7 (d, $^3J_{C,P}$ = 13 Hz, C-6b), 116.5 (d, $^3J_{C,P}$ = 12 Hz, C-6a), 117.7 (C-8b), 118.0 (C-8a), 125.7 (C_{phenyl}), 126.7 (C_{phenyl}), 127.8 (C_{phenyl}), 127.9 (C_{phenyl}), 128.3 (C_{phenyl}), 128.5 (C-7b), 129.0 (C_{phenyl}), 129.1 (C-7a), 129.3 (C_{phenyl}), 143.9 ($C_{q\text{-}phenyl}$-b), 146.6 ($C_{q\text{-}phenyl}$-a), 147.1 (d, $^2J_{C,P}$ = 14 Hz, C_q-a), 147.3 (d, $^2J_{C,P}$ = 14 Hz, C_q-b) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 105.8 ppm (**L1**): 90.2 ppm (**L12**); ratio 1:1.1. HRMS: calculated: 429.2334; found: 429.2336.

Borane Complex of M1 (containing ligands L1 and L12): BH_3·THF (1 M solution, 3 mL) was added dropwise by syringe to a solution of **M1** (0.558, 1.3 mmol) in toluene (5 mL), and the mixture was stirred at room temperature overnight. The volatiles were removed in vacuo and the yellowish solid was purified by flash chromatography over neutral alumina (eluent: pentane/ethyl acetate 5:1). The product was obtained as a colourless solid, which is stable towards air and moisture: 0.518 g, 90% yield.



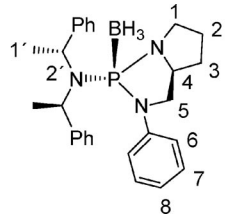
L1.BH$_3$: *S,R,R,R*p



L12.BH$_3$: *S,R,R,S*p

$^{31}P\{^1H\}$ NMR ($CDCl_3$): δ = 100.0 (**L1**·BH_3) and 87.4 (**L12**·BH_3) ppm.

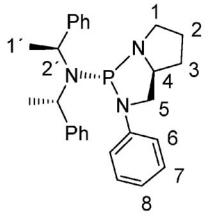
Isolation of L1·BH$_3$ by Crystallisation: The diastereomeric mixture **M1·BH$_3$** (268 mg, 0.6 mmol) was dissolved in $CHCl_3$ (5 mL) and cold pentane was added dropwise. After addition of pentane (25 mL), colourless crystals started to precipitate. The solution was kept at –30 °C overnight. After filtration, **L1·BH$_3$** was collected as a colourless solid (40 mg, yield 15%). Crystals for X-ray measurements were obtained by slow diffusion of pentane into a $CDCl_3$ solution.



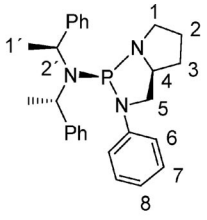
^1H NMR (C_6D_6): δ = 1.07–1.17 (m, 1 H, 3-H), 1.16–1.32 (m, 3 H, BH_3-H), 1.22 (d, $^3J_{H,H}$ = 7 Hz, 1′-H, 3′-H), 1.31–1.50 (m, 2 H, 2-H), 1.74–1.89 (m, 1 H, 3-H), 2.59–2.91 (m, 3 H, 1-H, 5-H), 3.08–3.23 (m, 1 H, 5-H), 3.87–4.03 (m, 1 H, 4-H), 4.91–5.10 (m, 2 H, 2′-H, 4′-H), 6.90 (t, $^3J_{H,H}$ = 7.6 Hz, 8-H), 6.96–7.28 (m, 12 H, H_{phenyl}, 6-H), 7.35–7.48 (m, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 20.2 (C-1′), 25.9 (d, $^3J_{C,P}$ = 3 Hz, C-2), 32.1 (C-3), 46.1 (d, $^2J_{C,P}$ = 11 Hz, C-1), 51.9 (d, $^2J_{C,P}$ = 3 Hz, C-2′), 60.3 (C-4), 119.2 (d,

$^3J_{C,P}$ = 5 Hz, C-6), 121.5 (C-8), 127.3 (C_{phenyl}), 128.4 (C_{phenyl}), 128.9 (C-7), 129.0 (C_{phenyl}), 142.5 (d, $^2J_{C,P}$ = 4 Hz, C_q), 143.7 ($C_{q\text{-}phenyl}$) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 101.4 (m) ppm.

Diastereomeric Mixture M2 (containing L2 and L13): The same procedure as before was used, but (*S*,*S*)-**2** was used for the synthesis instead of (*R*,*R*)-**2**. The product is a colourless solid that is sensitive towards air and moisture, but can be stored in cold conditions under inert atmosphere for several months: 1.265 g (95% yield).



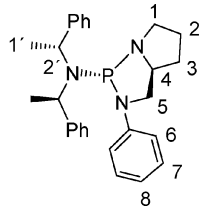
L2: *S,S,S,Sp*



L13: *S,S,S,Rp*

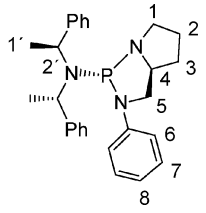
^{13}C NMR (C_6D_6): δ = 21.4 (d, $^3J_{C,P}$ = 11 Hz, C-1′, **L13**), 21.5 (d, $^3J_{C,P}$ = 12 Hz, C-1′, **L2**), 25.9 (C-2, **L2**), 28.3 (C-2, **L13**), 29.0 (C-3, **L13**), 32.6 (C-3, **L2**), 41.9 (d, $^2J_{C,P}$ = 17 Hz, C-5, **L13**), 49.5 (d, $^2J_{C,P}$ = 42 Hz, C-1, **L2**), 50.1 (d, $^2J_{C,P}$ = 3 Hz, C-1, **L13**), 52.8 (d, $^2J_{C,P}$ = 8 Hz, C-2′, **L13**), 53.3 (d, $^2J_{C,P}$ = 9 Hz, C-2′, **L2**), 54.9 (d, $^2J_{C,P}$ = 5 Hz, C-5, **L2**), 61.6 (d, $^2J_{C,P}$ = 8 Hz, C-4, **L2**), 63.5 (d, $^2J_{C,P}$ = 8 Hz, C-4, **L13**), 116.1 (d, $^3J_{C,P}$ = 12 Hz, C-6, **L2**), 116.5 (d, $^3J_{C,P}$ = 13 Hz, C-6, **L13**), 118.0 (C-8, **L13**), 126.6 (C_{phenyl}, **L13**), 126.9 (C_{phenyl}, **L2**), 128.0 (C_{phenyl}, **L2** and C_{phenyl}, **L13**), 128.9 (C-7, **L2**), 129.0 (C_{phenyl}, **L2**), 129.1 (C-7, **L13**), 129.3 (C_{phenyl}, **L13**), 143.8 ($C_{q\text{-}phenyl}$, **L13**), 146.6 ($C_{q\text{-}phenyl}$, **L2**), 146.8 (d, $^2J_{C,P}$ = 15 Hz, C_q, **L2**), 147.9 (d, $^2J_{C,P}$ = 12 Hz, C_q, **L13**) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 108.8 (**L2**): 86.4 (**L13**) ppm; ratio 1:3. HRMS: calculated: 429.2334; found: 429.2325.

(3a*S*)-2-Phenyl-*N*,*N*-bis[(*R*)-1-phenylethyl]-hexahydro-1*H*-pyrrolo-[1,2-*c*][1,3,2]diazaphosphol-1-amine (L1): In a 100 mL Schlenk flask, (*R*,*R*)-bis(1-phenylethyl)amine (1.113 g, 1.1 mL, 4.9 mmol) was dissolved in dry THF (10 mL), and the mixture was cooled down to –78 °C with a dry ice bath. *n*BuLi [3.1 mL (1.56 M in hexane), 4.8 mmol] was added dropwise and the solution was stirred for 30 min. Afterwards, **7** (1.19 g, 4.9 mmol) was added dropwise by syringe as a THF solution (10 mL). The mixture was allowed to warm to room temperature and stirred overnight, during which a colourless precipitate formed. The solvent was then removed and toluene (15 mL) was added. The precipitated LiCl was filtered off over a short pad of alumina (ca. 5 cm, Ø = 3 cm) and the column was washed twice with toluene (10 mL). The product (2.008 g, 95% yield) was obtained as transparent oil after removal of the solvent in vacuo.



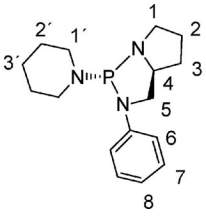
^1H NMR (C_6D_6): δ = 1.14–1.22 (m, 1 H, 3-H), 1.41–1.51 (m, 2 H, 2-H), 1.52–1.58 (m, 1 H, 3-H), 1.61 (d, $^3J_{H,H}$ = 7.1 Hz, 6 H, 1′-H), 2.97–3.04 (m, 2 H, 1-H, 5-H), 3.39–3.46 (m, 1 H, 1-H), 3.73–3.78 (m, 1 H, 5-H), 3.78–3.84 (m, 1 H, 4-H), 4.42–4.49 (m, 2 H, 2′-H), 7.00 (t, $^3J_{H7,H8}$ = 7.3 Hz, 1 H, 8-H), 7.10–7.34 (m, 10 H, H_{phenyl}), 7.36 (d, $^3J_{H6,H7}$ = 8.3 Hz, 2 H, 6-H), 7.43 (dd, $^3J_{H7,H6}$ = 8.3, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 21.5 (d, $^3J_{C,P}$ = 12 Hz, C-1′), 25.9 (d, $^3J_{C,P}$ = 4 Hz, C-2), 32.6 (C-3), 49.5 (d, $^2J_{C,P}$ = 42 Hz, C-1), 54.0 (d, $^2J_{C,P}$ = 9 Hz, C-2′), 54.2 (d, $^2J_{C,P}$ = 7 Hz, C-5), 62.5 (d, $^2J_{C,P}$ = 8 Hz, C-4), 116.1 (d, $^3J_{C,P}$ = 12 Hz, C-6), 118.0 (C-8), 127.0 (C_{phenyl}), 128.1 (C_{phenyl}), 129.1 (C-7), 129.2 (C_{phenyl}), 146.6 ($C_{q\text{-}phenyl}$), 147.1 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 105.8 (**L1**): 90.2 (**L12**) ppm; ratio 20:1. HRMS: calculated: 429.2334; found: 429.2334.

(3a*S*)-2-Phenyl-*N*,*N*-bis[(*S*)-1-phenylethyl]-hexahydro-1*H*-pyrrolo-[1,2-*c*][1,3,2]diazaphosphol-1-amine (L2): The same procedure was applied as for **L1**, but (*S*,*S*)-bis(1-phenylethyl)amine was used as the monoamine. Quantities: (*S*,*S*)-bis(1-phenylethyl)amine: 1.133 g, 1.2 mL, 5.0 mmol; **7**: 1.21 g, 5.0 mmol; *n*BuLi: 3.2 mL (1.56 M in THF), 5.0 mmol. Product: colourless solid (1.793 g, 83% yield).



^1H NMR (C_6D_6): δ = 1.09–1.15 (m, 1 H, 3-H), 1.34–1.44 (m, 2 H, 2-H), 1.55–1.63 (m, 1 H, 3-H), 1.71 (d, $^3J_{H,H}$ = 6.8 Hz, 6 H, 1′-H), 2.63–2.68 (m, 1 H, 5-H), 2.98–3.05 (m, 1 H, 1-H), 3.34–3.41 (m, 1 H, 1-H), 3.47–3.53 (m, 1 H, 5-H), 3.69–3.74 (m, 1 H, 4-H), 4.36–4.43 (m, 2 H, 2′-H), 6.44 (d, $^3J_{H6,H7}$ = 7.6 Hz, 2 H, 6-H), 6.82 (t, $^3J_{H7,H8}$ = 7.3 Hz, 1 H, 8-H), 6.95 (m, 4 H, H_{phenyl}), 7.03–7.16 (m, 6 H, H_{phenyl}), 7.19 (dd, $^3J_{H6,H7}$ = 7.6, $^3J_{H6,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 21.5 (d, $^3J_{C,P}$ = 11 Hz, C-1′), 25.9 (C-2), 32.7 (C-3), 49.5 (d, $^2J_{C,P}$ = 41 Hz, C-1), 53.3 (d, $^2J_{C,P}$ = 10 Hz, C-2′), 54.9 (d, $^2J_{C,P}$ = 5 Hz, C-5), 61.6 (d, $^2J_{C,P}$ = 8 Hz, C-4), 116.1 (d, $^3J_{C,P}$ = 12 Hz, C-6), 118.0 (C-8), 126.9 (C_{phenyl}), 127.9 (C_{phenyl}), 128.9 (C-7), 129.0 (C_{phenyl}), 146.6 ($C_{q\text{-}phenyl}$), 146.8 (d, $^2J_{C,P}$ = 15 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 108.8 (**L2**): 86.5 (**L13**) ppm; ratio 15:1. HRMS: calculated: 429.2334; found: 429.2334.

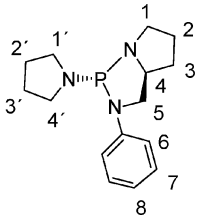
(3a*S*)-2-Phenyl-1-(piperidin-1-yl)-hexahydro-1*H*-pyrrolo[1,2-*c*]-[1,3,2]diazaphosphole (L3): Piperidine (0.5 mL, 0.43 g, 5.0 mmol) was added by syringe to a stirred solution of **7** (0.600 g, 2.5 mmol) in toluene (5 mL). The mixture was stirred at room temperature overnight. Afterwards, the colourless precipitate was removed by filtration through a short pad of neutral alumina (5 cm, Ø = 3 cm) and the column was washed twice with toluene (10 mL). The product (0.417 g, 58% yield) was obtained as a colourless solid after removal of the solvent in vacuo.



^1H NMR (C_6D_6): δ = 1.12–1.19 (m, 1 H, 3-H), 1.23–1.41 (m, 8 H, 2-H, 2′-H, 3′-H, 4′-H), 1.50–1.57 (m, 1 H, 3-H), 2.77–2.81 (m, 1 H, 5-H), 2.95–3.10 (m, 5 H, 1-H, 1′-H, 5′-H), 3.42–3.48 (m, 2 H, 1-H, 5-H), 3.71–3.76 (m, 1 H, 4-H), 6.97 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.24 (d, $^3J_{H6,H7}$ = 7.8 Hz, 2 H, 6-H), 7.39 (dd, $^3J_{H7,H6}$ = 7.8, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 25.5 (C-

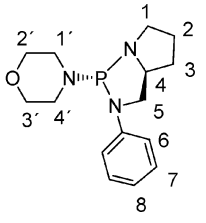
3′), 25.7 (d, $^3J_{C,P}$ = 5 Hz, C-2), 27.3 (d, $^3J_{C,P}$ = 5 Hz, C-2′), 32.4 (C-3), 46.3 (d, $^2J_{C,P}$ = 16 Hz, C-1′), 50.4 (d, $^2J_{C,P}$ = 40 Hz, C-1), 54.3 (d, $^2J_{C,P}$ = 7 Hz, C-5), 62.7 (d, $^2J_{C,P}$ = 8 Hz, C-4), 115.6 (d, $^3J_{C,P}$ = 12 Hz, C-6), 118.2 (C-8), 129.2 (C-7), 147.4 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 114.7 and 95.7 ppm; ratio 45:1. HRMS: calculated: 289.1708; found: 289.1670.

(3a*S*)-2-Phenyl-1-(pyrrolidin-1-yl)-hexahydro-1*H*-pyrrolo[1,2-*c*]-[1,3,2]diazaphosphole (L4): The same procedure was applied as for **L3**, but pyrrolidine was used for the synthesis instead of piperidine. Quantities: pyrrolidine: 0.42 mL, 0.356 g, 5.0 mmol; **7**: 0.600 g, 2.5 mmol. Product: colourless solid (0.406 g, 59% yield).



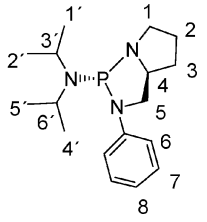
^1H NMR (C_6D_6): δ = 1.17–1.23 (m, 1 H, 3-H), 1.37–1.47 (m, 5 H, 2′-H, 3′-H, 2-H), 1.55–1.62 (m, 1 H, 3-H), 2.76–2.80 (m, 1 H, 5-H), 2.96–3.01 (m, 2 H, 1′-H, 4-H′), 3.03–3.09 (m, 1 H, 1-H), 3.14–3.19 (m, 2 H, 1′-H, 4′-H), 3.39–3.47 (m, 2 H, 5-H, 1-H), 3.78–3.83 (m, 1 H, 4-H), 6.84 (t, $^3J_{H8,H7}$ = 7.4 Hz, 1 H, 8-H), 7.06 (d, $^3J_{H6,H7}$ = 8.9 Hz, 2 H, 6-H), 7.27 (dd, $J_{H7,H6}$ = 8.9, $J_{H7,H8}$ = 7.4 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 25.8 (d, $^3J_{C,P}$ = 3 Hz, C-2′, C-3′), 26.5 (d, $^3J_{C,P}$ = 4 Hz, C-2), 32.4 (C-3), 46.6 (d, $^2J_{C,P}$ = 14 Hz, C-1′, C-4′), 50.8 (d, $^2J_{C,P}$ = 40 Hz, C-1), 54.7 (d, $^2J_{C,P}$ = 5 Hz, C-5), 63.1 (d, $^2J_{C,P}$ = 8 Hz, C-4), 115.2 (d, $^3J_{C,P}$ = 13 Hz, C-6), 118.0 (C-8), 129.3 (C-7), 147.4 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 107.3 and 91.7 ppm; ratio 80:1. HRMS: calculated: 275.1551; found: 275.1542.

4-[(3a*S*)-2-Phenyl-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphol-1-yl]morpholine (L5): The same procedure was applied as for **L3**, but morpholine was used for the synthesis instead of piperidine. Quantities: morpholine: 0.150 mL, 0.143 g, 1.66 mmol; **7**: 0.200 g, 0.83 mmol. Product: colourless solid (0.148 g, 61% yield).



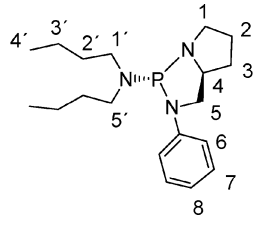
^1H NMR (C_6D_6): δ = 1.10–1.17 (m, 1 H, 3-H), 1.30–1.37 (m, 2 H, 2-H), 1.48–1.56 (m, 1 H, 3-H), 2.48 (m, 2 H, 2′-H), 2.70–2.74 (m, 1 H, 5-H), 2.82–2.99 (m, 3 H, 3′-H, 1-H), 3.31–3.44 (m, 4 H, 1-H, 5-H, 4′-H), 3.45–3.47 (m, 2 H, 1′-H), 3.57–3.64 (m, 1 H, 4-H), 6.86 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.06 (d, $^3J_{H6,H7}$ = 7.8 Hz, 2 H, 6-H), 7.26 (dd, $^3J_{H7,H6}$ = 7.8, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 25.7 (d, $^3J_{C,P}$ = 4 Hz, C-2), 32.3 (C-3), 45.6 (d, $^3J_{C,P}$ = 12 Hz, C-3′), 46.4 (C-2′), 50.3 (d, $^2J_{C,P}$ = 38 Hz, C-1), 54.4 (d, $^2J_{C,P}$ = 6 Hz, C-5), 62.8 (d, $^2J_{C,P}$ = 7 Hz, C-4), 67.7 (d, $^2J_{C,P}$ = 18 Hz, C-4′), 67.8 (d, $^2J_{C,P}$ = 6 Hz, C-1′), 115.6 (d, $^3J_{C,P}$ = 11 Hz, C-6), 118.5 (C-8), 129.2 (C-7), 147.0 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 114.5 and 95.0 ppm; ratio 90:1. HRMS: calculated: 291.1501; found: 291.1493.

(3a*S*)-*N*,*N*-Diisopropyl-2-phenyl-hexahydro-1*H*-pyrrolo[1,2-*c*]-[1,3,2]diazaphosphol-1-amine (L6): The same procedure was applied as for **L3**, but diisopropylamine was used for the synthesis instead of piperidine. Quantities: diisopropylamine: 0.47 mL, 0.336 g, 3.32 mmol; **7**: 0.400 g, 1.66 mmol. Product: colourless solid (0.441 g, 87% yield).



^1H NMR (C_6D_6): δ = 1.13 (d, $^3J_{H,H}$ = 7.1 Hz, 6 H, 1′-H, 2′-H), 1.14–1.19 (m, 1 H, 3-H), 1.25 (d, $^3J_{H,H}$ = 7.1 Hz, 6 H, 4′-H, 5′-H), 1.36–1.43 (m, 2 H, 2-H), 1.54–1.60 (m, 1 H, 3-H), 2.73–2.77 (m, 1 H, 5-H), 2.94–3.10 (m, 1 H, 1-H), 3.30–3.36 (m, 2 H, 3′-H, 6′-H), 3.36–3.42 (m, 1 H, 1-H), 3.52–3.55 (m, 1 H, 5-H), 3.69–3.75 (m, 1 H, 4-H), 6.83 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.16 (d, $^3J_{H6,H7}$ = 8.3 Hz, 2 H, 6-H), 7.27 (dd, $^3J_{H7,H6}$ = 8.3, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 23.7 (d, $^3J_{C,P}$ = 6 Hz, C-1′, C-2′), 24.8 (d, $^3J_{C,P}$ = 10 Hz, C-4′, C-5′), 25.7 (d, $^3J_{C,P}$ = 5 Hz, C-2), 32.6 (C-3), 45.3 (d, $^2J_{C,P}$ = 10 Hz, C-3′, C-6′), 49.5 (d, $^2J_{C,P}$ = 42 Hz, C-1), 54.7 (d, $^2J_{C,P}$ = 6 Hz, C-5), 61.8 (d, $^2J_{C,P}$ = 7 Hz, C-4), 116.0 (d, $^3J_{C,P}$ = 11 Hz, C-6), 118.1 (C-8), 129.0 (C-7), 147.2 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 107.0 ppm. HRMS: calculated: 305.2021; found: 305.2020.

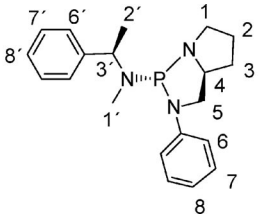
(3a*S*)-*N*,*N*-Dibutyl-2-phenyl-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphol-1-amine (L7): The same procedure was applied as for **L3**, but dibutylamine was used for the synthesis instead of piperidine. Quantities: dibutylamine: 0.28 mL, 0.214 g, 1.66 mmol; **1**: 0.200 g, 0.83 mmol. Product: colourless oil (0.255 g, 92% yield).



^1H NMR (C_6D_6): δ = 0.84 (t, $^3J_{H,H}$ = 7.3 Hz, 6 H, 4′-H), 1.10–1.30 (m, 5 H, 3′-H, 3-H), 1.31–1.46 (m, 6 H, 2′-H, 2-H), 1.53–1.64 (m, 1 H, 3-H), 2.81–2.86 (m, 1 H, 5-H), 2.88–2.95 (m, 2 H, 1′-H), 2.98–3.04 (m, 1 H, 1-H), 3.10 (m, 2 H, 5′-H), 3.44–3.50 (m, 1 H, 1-H), 3.52–3.56 (m, 1 H, 5-H), 3.78–3.83 (m, 1 H, 4-H), 6.82 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.05 (d, $^3J_{H6,H7}$ = 8.2 Hz, 2 H, 6-H), 7.26 (dd, $^3J_{H7,H6}$ = 8.2, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 14.1 (C-4′), 20.6 (C-3′), 25.9 (d, $^3J_{C,P}$ = 4 Hz, C-2), 31.4 (C-2′), 32.7 (C-3), 46.0 (d, $^2J_{C,P}$ = 18 Hz, C-1′, C-5′), 50.1 (d, $^2J_{C,P}$ = 43 Hz, C-1), 54.4 (d, $^2J_{C,P}$ = 7 Hz, C-5), 62.5 (d, $^2J_{C,P}$ = 8 Hz, C-4), 115.6 (d, $^3J_{C,P}$ = 12 Hz, C-6), 118.1 (C-8), 129.1 (C-7), 147.3 (d, $^2J_{C,P}$ = 14 Hz, C_q) ppm. $^{31}P\{^1H\}$ NMR (C_6D_6): δ = 118.2 and 97.6 (47:1) ppm. HRMS: calculated: 333.2334; found: 333.2331.

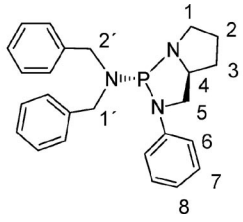
(3a*S*)-*N*-Methyl-2-phenyl-*N*-[(*R*)-1-phenylethyl]-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphol-1-amine (L8): DMAP (0.406 g, 3.32 mmol) was added to a stirred solution of **1** (0.800 g, 3.32 mmol) in toluene (5 mL), and the mixture was stirred for 10 min. (*R*)-*N*-Methyl-1-phenylethylamine (0.48 mL, 0.449 g, 3.32 mmol) was added neat by syringe, and the mixture was stirred overnight at room temperature. The formed colourless precipitate

was removed by filtration through a short pad of neutral alumina (5 cm, Ø = 3 cm) and the column was washed twice with toluene (10 mL). The product was obtained as a colourless oil after evaporation of the solvent in vacuo: 0.779 g, 70% yield.



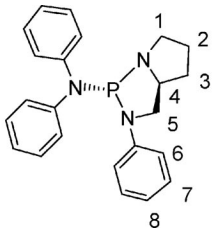
^{1}H NMR (C_6D_6): δ = 1.09–1.15 (m, 1 H, 3-H), 1.33–1.44 (m, 2 H, 2-H), 1.40 (d, $^3J_{H,H}$ = 7.0 Hz, 3 H, 2′-H), 1.49–1.55 (m, 1 H, 3-H), 2.18 (d, $^3J_{H,P}$ = 5.2 Hz, 3 H, 1′-H), 2.80–2.86 (m, 1 H, 5-H), 3.00–3.06 (m, 1 H, 1-H), 3.46–3.53 (m, 2 H, 5-H, 1-H), 3.69–3.72 (m, 1 H, 4-H), 4.88–4.95 (m, 1 H, 3′-H), 6.86 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.08 (t, $^3J_{H8',H7'}$ = 7.1 Hz, 1 H, 8′-H), 7.11 (d, $^3J_{H6,H7}$ = 8.7 Hz, 2 H, 6-H), 7.20 (m, 2 H, 7′-H), 7.28 (dd, $^3J_{H7,H6}$ = 8.7, $^3J_{H7,H8}$ = 7.3 Hz, 2 H, 7-H), 7.34 (d, $^3J_{H6',H7'}$ = 8.7 Hz, 2 H, 6′-H) ppm. ^{13}C NMR (C_6D_6): δ = 18.0 (d, $^3J_{C,P}$ = 7 Hz, C-2′), 25.9 (d, $^3J_{C,P}$ = 4 Hz, C-2), 26.9 (C-1′), 32.7 (C-3), 50.2 (d, $^2J_{C,P}$ = 40 Hz, C-1), 54.3 (d, $^2J_{C,P}$ = 7 Hz, C-5), 56.0 (d, $^2J_{C,P}$ = 36 Hz, C-3′), 62.7 (d, $^2J_{C,P}$ = 8 Hz, C-4), 115.8 (d, $^3J_{C,P}$ = 13 Hz, C-6), 118.3 (C-8), 126.7 (C-8′), 127.6 (C-6′), 128.3 (C-7′), 129.2 (C-7), 144.1 (d, $^2J_{C,P}$ = 3 Hz, $C_{q'}$), 147.0 (d, $^2J_{C,P}$ = 13 Hz, C_q) ppm. ^{31}P{^{1}H} NMR (C_6D_6): δ = 118.5/97.8 (115:1) ppm. HRMS: calculated: 339.1864; found: 339.1863.

(3a*S*)-*N*,*N*-Dibenzyl-2-phenyl-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphol-1-amine (L9): The same procedure was applied as for **L8**, but dibenzylamine was used for the synthesis instead of (*R*)-*N*-methyl-1-phenylethanamine. Quantities: dibenzylamine: 0.160 mL, 0.163 g, 0.83 mmol; **7**: 0.200 g, 0.83 mmol; DMAP: 0.101 g, 0.83 mmol. Product: colourless oil that solidifies upon standing (0.252 g, 76% yield).



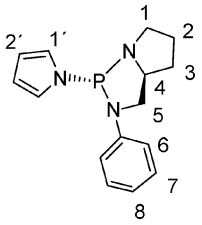
^{1}H NMR (C_6D_6): δ = 1.21–1.29 (m, 1 H, 3-H), 1.48–1.57 (m, 2 H, 2-H), 1.61–1.69 (m, 1 H, 3-H), 2.79–2.87 (m, 1 H, 5-H), 3.13–3.20 (m, 1 H, 1-H), 3.51–3.61 (m, 2 H, 1-H, 5-H), 3.77–3.84 (m, 1 H, 4-H), 3.91 (dd, $^2J_{H,H}$ = 15.5, $^3J_{H,P}$ = 10.7 Hz, 2 H, 1′-H, 2′-H), 4.33 (dd, $^2J_{H,H}$ = 15.5, $^3J_{H,P}$ = 6.7 Hz, 2 H, 1′-H, 2′-H), 6.90 (t, $^3J_{H8,H7}$ = 7.3 Hz, 1 H, 8-H), 7.06–7.12 (m, 4 H, 6-H, H_{arom}), 7.13–7.19 (m, 6 H, 7-H, H_{arom}), 7.28–7.31 (m, 4 H, H_{arom}) ppm. ^{13}C NMR (C_6D_6): δ = 25.9 (d, $^3J_{C,P}$ = 5 Hz, C-2), 32.5 (C-3), 50.0 (d, $^2J_{C,P}$ = 18 Hz, C-1′, C-2′), 50.2 (d, $^2J_{C,P}$ = 40 Hz, C-1), 54.5 (d, $^2J_{C,P}$ = 7 Hz, C-5), 62.3 (d, $^2J_{C,P}$ = 7 Hz, C-4), 116.0 (d, $^3J_{C,P}$ = 13 Hz, C-6), 118.5 (C-8), 126.9 (C_{arom}), 127.2 (C_{arom}), 128.3 (C_{arom}), 129.3 (C-7), 142.2 (d, $^2J_{C,P}$ = 8 Hz, $C_{q,arom}$), 146.9 (d, $^2J_{C,P}$ = 15 Hz, C_q) ppm. ^{31}P{^{1}H} NMR (C_6D_6): δ = 118.8/96.6 (68:1) ppm. HRMS: calculated: 401.2021; found: 401.2025.

(3a*S*)-*N*,*N*,2-Triphenyl-hexahydro-1*H*-pyrrolo[1,2-*c*][1,3,2]diazaphosphol-1-amine (L10): The same procedure was applied as for **L1**, but diphenylamine was used as the monoamine. Quantities: diphenylamine: 0.340 g, 2.0 mmol; **7**: 0.500 g, 2.0 mmol; *n*BuLi: 1.25 mL (1.6 M in hexane), 2.0 mmol. Product: colourless solid (0.420 g, 55% yield).



^{1}H NMR (C_6D_6): δ = 0.86–0.92 (m, 1 H, 3-H), 1.23–1.36 (m, 3 H, 2-H, 3-H), 2.49–2.58 (m, 1 H, 5-H), 2.69–2.75 (m, 1 H, 5-H), 2.91–3.03 (m, 2 H, 1-H, 4-H), 6.78 (t, $^3J_{H8,H7}$ = 7.4 Hz, 1 H, 8-H), 6.79–6.83 (m, 2 H, H_{arom}), 7.02 (d, $^3J_{H6,H7}$ = 8.6 Hz, 2 H, 6-H), 7.05–7.08 (m, 2 H, H_{arom}), 7.16 (dd, $^3J_{H7,H6}$ = 8.6, $^3J_{H7,H8}$ = 7.4 Hz, 2 H, 7-H), 7.07–7.11 (m, 4 H, H_{arom}), 7.23–7.27 (m, 2 H, H_{arom}) ppm. ^{13}C NMR (C_6D_6): δ = 26.1 (C-2), 32.4 (C-3), 49.8 (d, $^2J_{C,P}$ = 41 Hz, C-1), 54.1 (d, $^2J_{C,P}$ = 5 Hz, C-5), 62.3 (d, $^2J_{C,P}$ = 8 Hz, C-4), 115.8 (d, $^3J_{C,P}$ = 13 Hz, C-6), 116.2 (d, $^3J_{C,P}$ = 4 Hz, C_{arom}), 118.8 (C-8), 123.6 (C_{arom}), 124.9 (d, $^3J_{C,P}$ = 7.7 Hz, C_{arom}), 129.3 (C_{arom}), 129.4 (C-7), 146.8 (d, $^2J_{C,P}$ = 17 Hz, C_q), 146.8 (d, $^2J_{C,P}$ = 10 Hz, $C_{q\text{-}arom}$) ppm. ^{31}P{^{1}H} NMR (C_6D_6): δ = 103.2 and 90.6 ppm; ratio 100:1.

(3a*S*)-2-Phenyl-1-(1*H*-pyrrol-1-yl)-hexahydro-1*H*-pyrrolo[1,2-*c*]-[1,3,2]diazaphosphole (L11): The same procedure was applied as for **L1**, but pyrrole was used as the monoamine. Quantities: pyrrole: 0.14 mL, 0.135 g, 2.0 mmol; **7**: 0.500 g, 2.0 mmol; *n*BuLi: 1.25 mL (1.6 M in THF), 2.0 mmol. Product: colourless solid (0.488 g, 90% yield).



^{1}H NMR (C_6D_6): δ = 1.03–1.09 (m, 1 H, 3-H), 1.17–1.27 (m, 2 H, 2-H), 1.35–1.43 (m, 1 H, 3-H), 2.61–2.66 (m, 1 H, 5-H), 2.76–2.83 (m, 1 H, 1-H), 3.09–3.17 (m, 1 H, 1-H), 3.19–3.24 (m, 1 H, 5-H), 3.70–3.74 (m, 1 H, 4-H), 6.39–6.42 (m, 2 H, 2′-H), 6.75 (t, $^3J_{H8,H7}$ = 7.4 Hz, 2 H, 8-H), 6.86 (d, $^3J_{H6,H7}$ = 7.8 Hz, 2 H, 6-H), 7.00–7.03 (m, 2 H, 1′-H), 7.08 (dd, $^3J_{H7,H6}$ = 7.8, $^3J_{H7,H8}$ = 7.4 Hz, 2 H, 7-H) ppm. ^{13}C NMR (C_6D_6): δ = 26.1 (d, $^3J_{C,P}$ = 5 Hz, C-2), 31.2 (C-3), 49.4 (d, $^2J_{C,P}$ = 37 Hz, C-1), 53.6 (d, $^2J_{C,P}$ = 6 Hz, C-5), 63.1 (d, $^2J_{C,P}$ = 8 Hz, C-4), 111.5 (C-2′), 115.7 (d, $^3J_{C,P}$ = 13 Hz, C-6), 119.7 (C-8), 121.6 (d, $^2J_{C,P}$ = 14 Hz, C-1′), 129.5 (C-7), 145.4 (d, $^2J_{C,P}$ = 15 Hz, C_q) ppm. ^{31}P{^{1}H} NMR (C_6D_6): δ = 100.8/89.1 ppm; ratio 15:1. HRMS: calculated: 271.12384; found: 271.12380.

Catalysis

General Procedure for Cu-Catalysed Addition of Et_2Zn to Cyclohex-2-enone: [$(CuOTf)_2$·benzene] (2.6 mg, 0.005 mmol) was added to a ligand solution (0.011 mmol) in dry and degassed toluene (1 mL) and the resulting mixture was stirred for 1 h at room temperature until the Cu precursor had dissolved completely. The solution was then cooled down to the indicated temperature with a cryostat. After the temperature had stabilised, Et_2Zn (400 μL, 1 M in toluene,

0.4 mmol) was added by syringe and the resulting yellow solution was stirred for 10 min. Subsequently, cyclohex-2-enone (20 μL, 19.8 mg, 0.2 mmol) was added by syringe, and the mixture was stirred at the desired reaction temperature for the indicated time and finally quenched with saturated aqueous NH_4Cl (2 mL). The organic layer was washed with brine (2 mL) and distilled water (2 mL) and was dried with Na_2SO_4. From this solution, a sample (0.3 mL) was taken and diluted to 1 mL with toluene or dichloromethane (both HPLC grade) for GC analysis.

Conditions for Gas Chromatography: Carrier gas: H_2 (0.6 bar); column: Lipodex E (25 m); temperature program: 90 °C isotherm; detector: FID; retention times: cyclohex-2-enone 6.0 min, (*S*)-3 ethylcyclohexanone 6.4 min, (*R*)-3-ethylcyclohexanone 6.8 min.

General Procedure for Ni-Catalysed Hydrovinylation of Styrene: Under argon, a solution of the PTA ligand (0.012 mmol) in CH_2Cl_2 (1.5 mL) was added by syringe to a solution of $[Ni(allyl)Br]_2$ (2.0 mg, 0.006 mmol) in the same solvent (1.5 mL). The mixture was cooled down to the temperature indicated in Table 5 and styrene (0.41 mL, 3.6 mmol) was added by syringe. The resulting solution was first purged with ethene and then maintained under ethene. NaBARF (12 mg, 0.013 mmol) was added and the reaction mixture was stirred for the indicated time. Afterwards, the mixture was quenched with saturated aqueous ammonia, ethylbenzene (0.41 mL, 3.4 mmol) was added, and the organic phase was washed with brine and dried with Na_2SO_4. Finally the slightly yellow organic phase was filtered through a short pad of silica and analysed by GC. For determination of the degree of conversion the sample was injected undiluted. For determination of enantioselectivity, a portion of the organic phase (0.1 mL) was diluted with HPLC-grade CH_2Cl_2 (1 mL) before injection.

Gas-Chromatographic Conditions for Determination of the Conversion: Carrier gas: N_2 (1.3 bar); temperature program: 50 °C, 5 min/8 °C min^{-1}/230 °C, 20 min; column: Cp-Sil-Pona (50 m); detector: FID; internal standard: ethylbenzene. Retention times: ethylbenzene: 15.6 min, styrene: 16.4 min, 3-phenylbut-1-ene: 20.1 min, (*E*)-2-phenylbut-1-ene: 20.5 min, (*Z*)-2-phenylbut-1-ene: 22.8 min, oligomers (FW: 160 g mol^{-1}): 24.5–25.3 min, oligomers (FW: 208 g mol^{-1}): 35.7 and 41.3 min, oligomers (FW: 236 g mol^{-1}): 38.1–38.9 min. The compounds were identified by GC-MS.

Gas-Chromatographic Conditions for Determination of the Enantioselectivity: Carrier gas: H_2 (1 bar); temperature program: 60 °C/1 °C min^{-1}/85 °C/20 °C min^{-1}/180 °C, 5 min; column: Pb-OV5 (25 m) + Lipodex 7 (25 m); detector: FID. Retention times: (*R*)-3-phenylbut-1-ene: 15.9 min, (*S*)-3-phenylbut-1-ene: 16.2 min, (*E*)-*and* (*Z*)-2-phenylbut-1-ene: 16.7 min.

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