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Binaphthyl–prolinol chiral ligands: design and their application in enantioselective arylation of aromatic aldehydes†

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Binaphthyl–prolinol ligands were designed and applied in enantioselective arylation of aromatic aldehydes and sequential arylation–lactonization of methyl 2-formylbenzoate. Under optimized conditions, the reactions provided the desired diarylmethanols and 3-aryl phthalides in up to 96% yields with up to 99% ee and up to 89% yields with up to 99% ee, respectively. In particular, essentially optically pure 3-aryl phthalides (over 99% ee) were obtained in large quantities through recrystallization.

1. Introduction

1,1′-Binaphthyl-2,2′-diol (BINOL) has played important roles in asymmetric synthesis. So far, a variety of new ligands/catalysts have been developed using BINOL as the starting material.[1] As a consequence, the binaphthyl skeleton has been regarded as one of the most important privileged structures in the design of new chiral ligands.[2] Similarly, excellent performance was also observed when proline derivatives and related structures were used as chiral ligands/catalysts in a variety of asymmetric organic reactions.[3] It is our aim to develop new chiral ligands using the privileged structure strategy, and to apply the newly developed chiral ligands in different asymmetric organic reactions. Herein, we wish to report our recent progress in the synthesis and structure optimization of new binaphthyl–prolinol ligands, and the application of these ligands in enantioselective transfer of aryl groups to different carbonyl compounds.

Chiral diarylmethanols are important intermediates for bioactive compounds and pharmaceuticals[4] such as antihistamines (*R*)-orphenadrine, (*R*)-neobenodine,[5] or (*S*)-cetirizine (Fig. 1),[6] and enantioselective reduction of prochiral diaryl ketones or enantioselective addition of aryl agents to aromatic aldehydes could be regarded as one of the most straightforward methods for the preparation of such compounds.[7] The latter has been realized *via* direct addition of aryl Grignard reagents or other aryl organometallics to aromatic aldehydes, or using relatively mild arylboronic acids as aryl surrogates.[8] In the presence of a proper chiral catalyst, enantioselective aryl transfer to aromatic aldehydes would provide products with good enantioselectivity and high yields using arylboronic acid as the aryl source.[9]

2. Results and discussion

Enantioselective addition of diphenylzinc to aromatic aldehydes was reported by Fu *et al.*[10] Later, Miyaura *et al.* reported the enantioselective addition of organoboronic acids to aldehydes.[11] Compared with organozinc reagents, arylboronic acids were easy to handle, and the reactions could be carried out under mild conditions. The well documented features of this reaction make it an ideal method for the preparation of optically active diarylmethanols as well as an ideal model to evaluate the strategy of chiral catalyst design.[12]

In our previous report, we have shown that, a combination of a binaphthyl skeleton and other chiral elements would provide chiral ligands with good performance. For example, chiral ligands **1** incorporating binaphthyl and prolinols or chiral ligands **2** incorporating binaphthyl and chiral oxazolines could all be used in enantioselective addition of diethylzinc to aromatic aldehydes.[13] In particular, excellent ee's were observed when (R_a,*S*)-**1a** was used as the chiral ligand (Fig. 2).[13]

However, low ee's were obtained when these chiral ligands were extended to enantioselective transfer of aryl agents to aromatic aldehydes.[14] While ligands **1** showed some sort of structure-dependent stereoselectivity using Bolm's protocol as a standard method,[9] ligands **2** did not show any stereoselectivity at all (Table 1).

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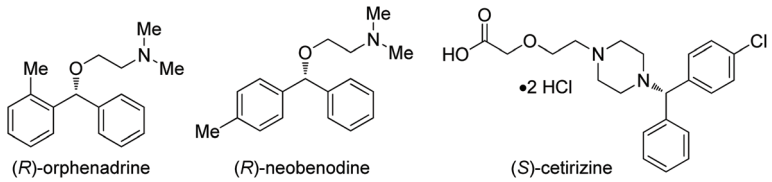


Fig. 1 Structures of bioactive diarylmethanol derivatives.

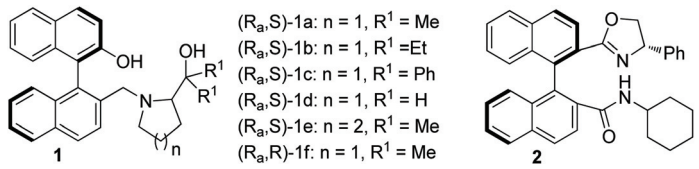
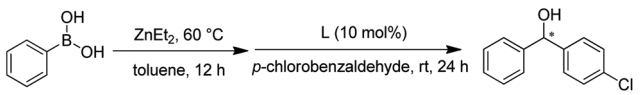


Fig. 2 Previously reported binaphthyl-based chiral ligands **1** and **2**.

Table 1 Catalytic asymmetric phenyl transfer to *p*-chlorobenzaldehyde[a]



Entry	Ligand	Yield[b] (%)	ee[c] (%)	Config.[d]
1	**1a**	78	8	*R*
2	**1b**	81	22	*R*
3	**1c**	83	37	*R*
4	**1d**	54	4	*R*
5	**1e**	82	6	*R*
6	**1f**	60	0	*R*
7	**2**	64	0	*R*

[a] Conditions: reactions were performed on a 0.25 mmol scale. PhB$(OH)_2$ (2.4 equiv.) and Et_2Zn (7.2 equiv.) were stirred in toluene at 60 °C for 12 h. The chiral ligand and *p*-chlorobenzaldehyde were then added to the solution. The reaction mixture was stirred at room temperature for 24 h. [b] Isolated yields. [c] The ee values were determined by HPLC (Chiralcel AD-H column, *n*-hexane : isopropanol = 95 : 5, 1 mL min^{-1}, UV = 220 nm). [d] Absolute configuration was assigned by comparison to the reported value and sign of specific rotation of the product.[15]

The results in Table 1 suggest that increasing the bulkiness at the prolinol side of chiral ligands **1** had some impact on the stereoselectivity of the reaction, and ligand **1c** provided the highest ee among the ligands tested (Table 1, entries 1 to 3). We envisioned that the stereoselectivity of the chiral ligands could be further improved when an appropriate substituent is introduced to the binaphthyl part of the chiral ligands.

In their pioneering work, Trost *et al.* proposed a di-zinc model to interpret the enantioselectivity of a proline-based catalyst (Fig. 3).[16] Our previous study also suggested that a **1c**-type chiral ligand also tended to possess a di-zinc form during the reaction. In this model, one zinc atom possessed a distorted tetrahedral four-coordinate structure to lock the conformation of the catalyst, and another zinc atom possessed a planar three-coordination structure which provided an additional site for substrate binding.[13] Careful examination of the computer model suggested that the coordination site could be significantly affected when an appropriate substituent is introduced to the 3-possition which is adjacent to the hydroxyl group of the chiral ligands (Fig. 3, R^2 in ligand **3**).

To test this assumption, a synthetic route to chiral ligand **3** was proposed using (*R*)-BINOL as a general starting material (Scheme 1).[13] In our previous report, we have established the preparation of 2-methoxy-2′-methyl-1,1′-binaphthalene (**4**) from BINOL. Lithiation at the 3-position followed by reaction with iodine furnished compound **5**. Cu(I)-Catalyzed coupling of **5** with methyl fluorosulfonyldifluoroacetate (MFSDA) gave 2-methoxy-2′-methyl-3-trifluoromethyl-1,1′-binaphthalene (**6**) which could be converted to 2′-bromomethyl-2-methoxy-3-trifluoromethyl-1,1′-binaphthalene (**7**) *via* free radical substitution. Subsequent reaction between **7** and different prolinols gave compounds **8** which combined both the binaphthyl moiety and the prolinol moiety. However, demethylation of **8** was found to be difficult, and the desired product **3** could not be obtained in a reasonable yield in a preliminary test of demethylation of **8** (Scheme 1).

The preliminary results indicate that replacing the 2-methoxyl group with another protective group is necessary to facilitate the deprotection processes, and 3-acetate would be a good choice due to its ease of removal. Next, a different route was proposed starting from 3-iodo-2-methoxy-2′-methyl-1,1′-binaphthalene (**5**). Cleavage of the methyl ether with BBr_3 produced 3-iodo-2′-methyl-[1,1′-binaphthalen]-2-ol (**9**) which could be converted to the corresponding acetate **12a** in good yield. Cu(I)-Catalyzed coupling of **12a** with methyl fluorosulfonyldifluoroacetate (MFSDA) gave 2-acetoxy-2′-methyl-3-trifluoromethyl-1,1′-binaphthalene **12**. Alternatively, compound **10** could be synthesized *via* coupling of **5** with PhMgBr, and intermediate **12c** could be obtained *via* demethylation with BBr_3 and subsequent acetylation of **11**. Finally, free radical bromination of **12** gave 2′-bromomethyl intermediate **13**, which could be readily converted to intermediate **14**. Deacetylation of **14** led to the preparation of the desired chiral ligands **3a–3h** (Scheme 2).

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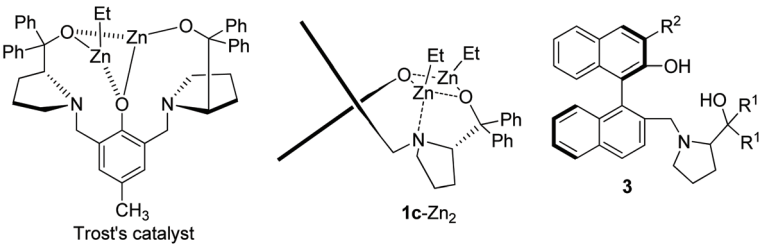
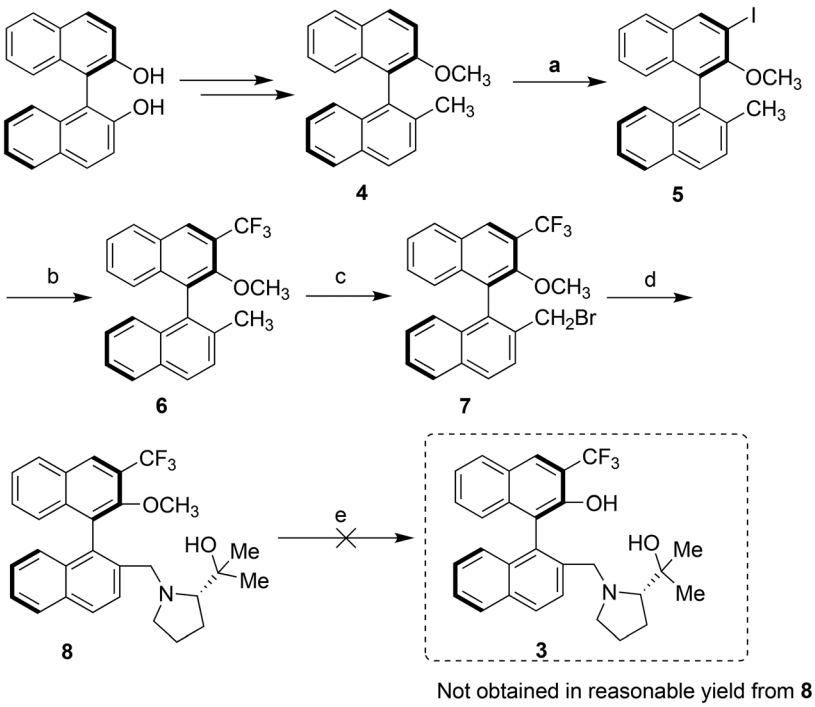


Fig. 3 Representative proline-based chiral ligands.



Scheme 1 Preliminary preparation of chiral ligands *via* the 2-methoxyl protocol. Results and conditions: (a) *n*-BuLi, TMEDA, then I_2, 0 °C, THF, 2 h, 47%; (b) CuI, MFSDA, HMPA, DMF, 70 °C, 8 h, 71%; (c) NBS, AIBN, DCE, 80 °C, 6 h, 71%; and (d) ((*S*)-2-(pyrrolidin-2-yl) propan-2-ol, K_2CO_3, NaI, CH_3CN, 16 h, 66%.

With the new ligands **3a–3h** in hand, the application of these ligands in the arylation of *p*-chlorobenzaldehyde was tested using phenylboronic acid as the phenyl source. The preliminary results in Table 2 reveal that the introduction of different substituents at the C-3 position significantly improved the enantioselectivity of the reactions, and the 3-trifluoromethyl substituted ligand **3f** gave the most promising result. The results from **3e** and **3g** suggested that the stereofacial selection of the reaction was mainly governed by the prolinol moiety, and that the matching between the central chirality of the amino alcohol and axial chirality was important as well (Table 2, entries 5 and 8).

Next, the reaction conditions were optimized using **3f** as the chiral ligand.[17] Previously reported protocols were adopted. The preliminary results are shown in Table 3. They suggest that the most suitable amount of chiral ligand was 10 mol%, and the most suitable solvent was toluene (Table 3, entries 1 to 4). The reaction was carried out on a 0.25 mmol scale at 0 °C for 24 h. Both DiMPEG 2000 and DiMPEG 500 were effective additives, and the ee's could be further improved upon addition of these polyethers, possibly due to the suppression of the unwanted nonasymmetric pathways by these additives through deactivating the (achiral) metal catalysts and preventing their nonenantioselective contribution to the overall process.[14a] DiMPEG 2000 was finally chosen as the additive due to its ease of handling.

After the optimization of the reaction conditions, different substrates were tested to study the scope of the reaction (Table 4).[18] Gratifyingly, good to excellent yields (74–96%) and good to excellent enantioselectivities (81–99% ee) were

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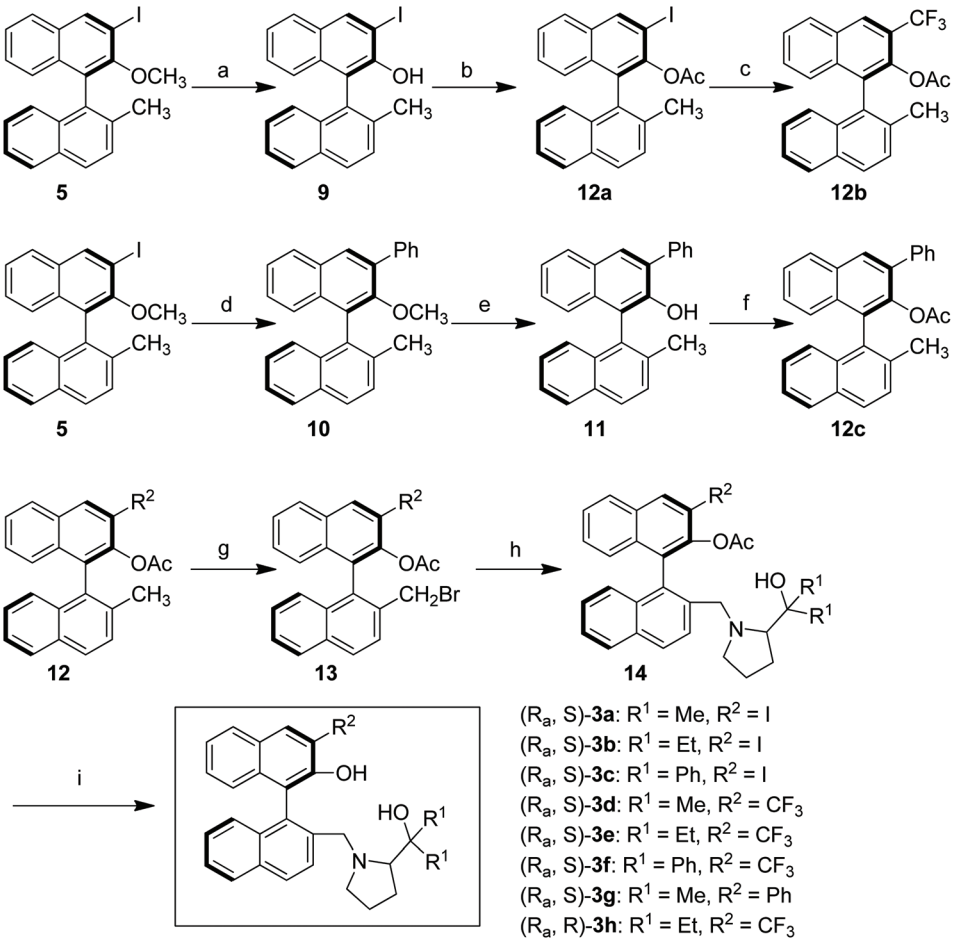
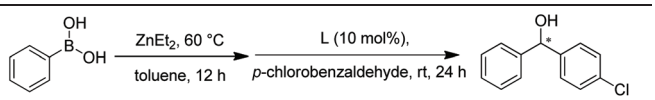


Scheme 2 Preparation of chiral ligands **3**. Results and conditions: (a) BBr_3, DCM, 0 °C, 1 h, 99%; (b) Ac_2O, pyridine, 25 °C, 6 h, 99%; (c) CuI, MFSDA, HMPA, DMF, 70 °C, 8 h, 78%; (d) PhMgBr, $(NiCl_2)$dppp, THF, 60 °C, 12 h, 86%; (e) BBr_3, DCM, 0 °C, 1 h, 96%; (f) Ac_2O, pyridine, 25 °C, 6 h, 88%; (g) NBS, AIBN, DCE, 80 °C, 6 h, 58–75%; (h) amino alcohols, K_2CO_3, NaI, CH_3CN, 16 h, 48–82%; and (i) NaOH, MeOH, 75 °C, 3 h, 81–95%.

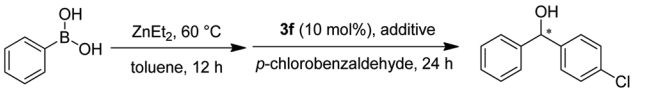
Table 2 Catalytic asymmetric phenyl transfer to *p*-chlorobenzaldehyde[a]



Entry	Ligand	Yield[b] (%)	ee[c] (%)	Config.[d]
1	**3a**	87	23	*R*
2	**3b**	62	35	*R*
3	**3c**	70	38	*R*
4	**3d**	82	54	*R*
5	**3e**	87	73	*R*
6	**3f**	96	88	*R*
7	**3g**	35	22	*R*
8	**3h**	82	43	*S*

[a] Conditions: reactions were performed on a 0.25 mmol scale with $PhB(OH)_2$ (2.4 equiv.) and Et_2Zn (7.2 equiv.) in toluene (stirring at 60 °C for 12 h), followed by the addition of the ligand and aldehyde, with stirring for 24 h. [b] Isolated yields. [c] The ee values were determined by HPLC. [d] Absolute configuration was assigned by comparison to the reported value and sign of specific rotation of the product.[15]

Table 3 Optimization of the reaction conditions for **3f**-promoted asymmetric phenyl transfer to *p*-chlorobenzaldehyde[a]



Entry	**3f** (mol%)	Solvent	Temp. (°C)	Yield[b] (%)	ee[c] (%)
1	10	Toluene	25	96	88
2	10	DCE	25	86	81
3	10	Xylene	25	83	86
4	10	Hexane	25	84	85
5[d]	10	Toluene	25	96	93
6[e]	10	Toluene	25	91	92
7[d]	20	Toluene	25	86	76
8[d]	5	Toluene	25	83	81
9[d]	10	Toluene	0	93	95
10[d]	10	Toluene	−10	88	91

[a] Reaction conditions: reactions were performed on a 0.25 mmol scale with $PhB(OH)_2$ (2.4 equiv.) and Et_2Zn (7.2 equiv.) in toluene (stirring at 60 °C for 12 h), followed by the addition of **3f**, the additive and aldehyde. Reaction time = 24 h. [b] Isolated yields. [c] The ee values were determined by HPLC (Chiralcel OD-H column). [d] In the presence of 10 mol% DiMPEG 2000. [e] In the presence of 10 mol% DiMPEG 500.

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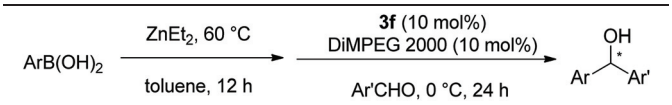
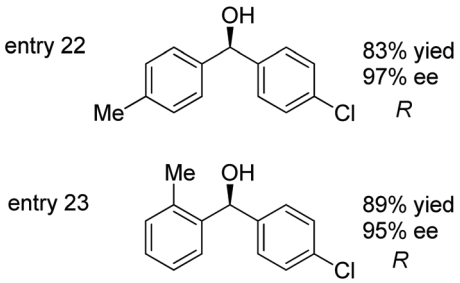
Table 4 Enantioselective arylation of aromatic aldehydes using **3f** as a chiral ligand[a]



Entry	Ar′ (Ar = Ph)	Yield[b] (%)	ee[c] (%)	Config.[d]
1	4-ClPh	96	95	*R*
2	4-BrPh	92	94	*R*
3	2-BrPh	95	96	*R*
4	4-MePh	90	98	*R*
5	3-MePh	89	95	*R*
6	2-MePh	88	98	*R*
7	3,4-DiMePh	95	94	*R*
8	4-MeOPh	91	98	*R*
9	3-MeOPh	96	99	*R*
10	2-MeOPh	92	94	*R*
11	4-CF_3Ph	74	92	*R*
12	1-Naphthyl	90	86	*R*
13	2-Naphthyl	86	97	*R*
14	2-Thienyl	92	97	*R*
15	2-Furyl	96	95	*R*
16	PhCH=CH–	78	91	*R*
17	4-BrPh	93	88	*S*
18	4-MePh	93	88	*S*
19	3-MePh	78	81	*S*
20	2-MePh	81	92	*S*
21	3-MeOPh	90	99	*S*



[a] Conditions: reactions were performed on a 0.25 mmol scale with PhB$(OH)_2$ (2.4 equiv.) and Et_2Zn (7.2 equiv.) in toluene (stirring at 60 °C for 12 h), followed by the addition of **3f** (10 mol%), DiMPEG 2000 (10 mol%) and aldehyde at 0 °C, with stirring for 24 h. [b] Isolated yields. [c] The ee values were determined by HPLC. [d] Absolute configurations were assigned by comparison to the reported values and signs of specific rotations of the products.[15,19]

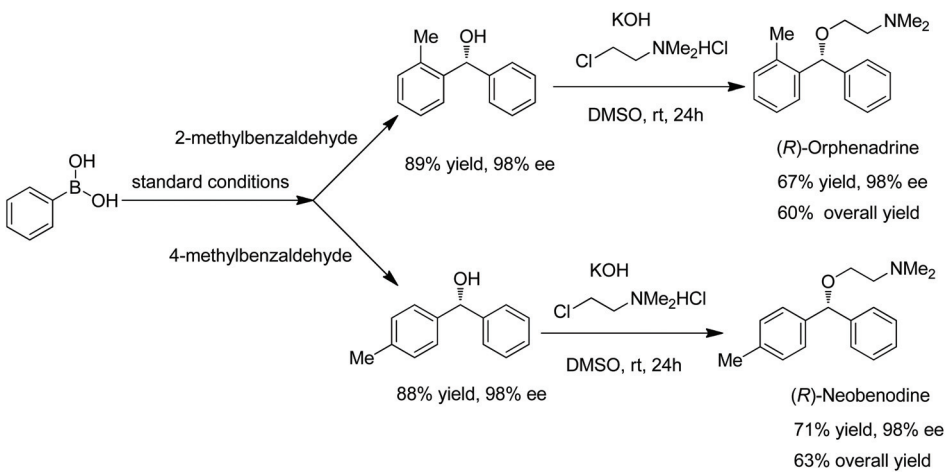
achieved for various aromatic aldehydes irrespective of the position and electronic nature of the substituents on the phenyl rings. Bulky aldehydes such as naphthaldehydes also gave the desired products in satisfactory yields (Table 4, entries 12 and 13). Heterocyclic aromatic rings displayed high enantioselectivity as well (Table 4, entries 14 and 15). In the presence of the same chiral ligand **3f**, both enantiomers of the corresponding diarylmethanols could be readily prepared with excellent yields and high enantioselectivities with the variation of the substituents on aldehyde and arylbronic acids[15,19] (Table 4, entries 2 *vs.* 17, 4 *vs.* 18, 5 *vs.* 19, 6 *vs.* 20 and 9 *vs.* 21). Chiral diarylmethanols containing two different substituted aryl groups could be easily synthesized with the combination of arylboronic acids and aromatic aldehydes (Table 4, entries 22 and 23).

To demonstrate the utility of the catalytic system, arylation of 2-methylbenzaldehyde and 4-methylbenzaldehyde was carried out at a 5 mmol scale, and the subsequent functional group transformation provided the important antihistamines (*R*)-orphenadrine and (*R*)-neobenodine in 60% overall yield with 98% ee and 63% overall yield with 98% ee, respectively (Scheme 3).

After the enantioselective arylation of different aromatic aldehydes, our attention turned to sequential arylation–lactonization of 2-formylbenzoates. 3-Aryl phthalides are important intermediates for organic synthesis and drug synthesis,[20] and an enantioselective arylation–lactonization cascade was proved to be an efficient route to this type of important compounds.[21]

Different arylboronic acids were subjected to enantioselective arylation–lactonization of methyl 2-formylbenzoate to test the scope of the substrates. The chiral ligand **3f** was tested in enantioselective arylation–lactonization of methyl 2-formylbenzoate under previously optimized conditions, and the reaction time was extended to 36 h to ensure high conversion of the substrates.

Representative results are shown in Table 5. To our delight, this protocol could serve as a general approach to different optically active 3-substituted phthalides, and the products could be obtained in good yields with excellent enantioselectivities. The electronic properties of aromatic rings had



Scheme 3 Preparation of antihistamines using chiral biarylmethanols as key intermediates.

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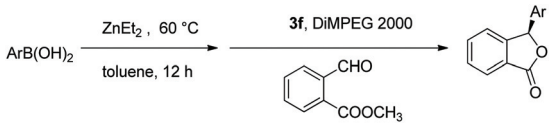
Table 5 The scope of arylation–lactonization reactions of methyl 2-formylbenzoate[a]



Entry	Ar	Yield[b] (%)	ee[c] (%)	Config.[d]
1	Ph	76 (81)[e]	95 (99)[f]	*R*
2	4-MePh	78 (70)[e]	97 (99)[f]	*R*
3	3-MePh	80 (76)[e]	98 (99)[f]	*R*
4	2-MePh	64 (76)[e]	94 (99)[f]	*R*
5	3-MeOPh	74	90	*R*
6	1-Naphthyl	65 (82)[e]	86 (99)[f]	*R*
7	4-BrPh	81 (93)[e]	97 (99)[f]	*R*
8	4-ClPh	81 (91)[e]	97 (99)[f]	*R*
9	3-ClPh	83 (88)[e]	94 (99)[f]	*R*
10	4-FPh	85 (83)[e]	96 (99)[f]	*R*
11	3-CF_3Ph	84	98	*R*
12	2,4-DiFPh	89 (92)[e]	91 (99)[f]	*R*
13	3-Thienyl	77	87	*R*

[a] Conditions: reactions were performed on a 0.25 mmol scale with PhB$(OH)_2$ (2.4 equiv.) and Et_2Zn (7.2 equiv.) in toluene (stirring at 60 °C for 12 h), followed by the addition of **3f** (10 mol%), DiMPEG 2000 (10 mol%) and aldehyde at 0 °C, with stirring for 36 h under an atmosphere of argon. [b] Isolated yields. [c] The ee values were determined by HPLC (Chiralcel OD-H column). [d] Absolute configurations were assigned by comparison to the reported values and signs of specific rotations of the products.[15] [e] In parentheses: the mass recovery after recrystallization. [f] In parentheses: the ee values after recrystallization.

little effect on the enantioselectivity of the reactions, and all the tested substituted aryl boronic acids gave satisfactory enantioselectivities with up to 98% ee (Table 4, entries 1–13).

The reactions were sensitive to the steric effect of the nucleophiles, and only 86% ee was observed when bulky 1-naphthaleneboronic acid was used (Table 5, entry 6). Aromatic heterocyclic boronic acid also gave good results with 77% yield and 87% ee values (Table 5, entry 13). The reaction could be carried out on a 1 mmol scale without the loss of enantioselectivity. Furthermore, the ee's of the products could be further improved to over 99% ee after simple recrystallization, demonstrating the application potential of this method for the preparation of important 3-substituted phthalides.

3. Conclusions

In summary, a series of new chiral ligands were designed, and were applied in enantioselective arylation of aromatic aldehydes as well as enantioselective arylation–lactonization of methyl 2-formylbenzoate. Under optimized conditions, the reactions provided the desired diarylmethanols and 3-aryl phthalides in up to 96% yields with up to 99% ee and up to 89% yields with up to 99% ee, respectively. The reaction could be carried out on a 5 mmol scale, and it could facilitate the asymmetric synthesis of optically pure antihistamines such as (*R*)-orphenadrine or (*R*)-neobenodine. Furthermore, 3-aryl phthalides with 99% ee could be easily obtained through recrystallization, revealing the application potential of the method in asymmetric synthesis of chiral aryl phthalides.

4. Experimental sections

4.1. General experimental information

Air-sensitive reactions were conducted in oven-dried glassware equipped with tightly fitted rubber septa and under a positive pressure of dry argon. Unless otherwise indicated, commercial reagents were used as received without further purification. Anhydrous dichloromethane was distilled from CaH_2 and toluene was distilled from sodium silk prior to use. ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ on a 400 MHz spectrometer at 298 K using tetramethylsilane (TMS) as an internal standard. Chemical shifts are reported in parts per million (ppm). Column chromatography separations were performed by employing 200–300 mesh silica gel. Melting points were measured on digital melting-point apparatus without correction of the thermometer. Infrared spectra were reported in wave number. HRMS spectra were obtained on a Varian FTICR-MS 7.0T mass spectrometer. HPLC analyses were carried out using Chiralcel OD-H, AD-H or OB-H.

4.2. Preparation of chiral ligands

(*R*)-3-Iodo-2-methoxy-2′-methyl-1,1′-binaphthalene (5). To a solution of (*R*)-2-methoxy-2′-methyl-1,1′-binaphthalene **4** (5.00 g, 16.8 mmol) in THF (100 mL) was added dropwise *n*-BuLi (15.6 mL, 42.0 mmol, 2.7 M solution in *n*-heptane) at −78 °C for 30 min. The mixture was warmed to 0 °C and stirred for 2 h. The mixture was treated with iodine (10.66 g, 42.0 mmol) at −78 °C. After stirring for an additional 1 h, saturated aqueous solution of Na_2SO_3 was added. The aqueous phase was extracted with ethyl acetate (100 mL × 3) and the combined organic layer was washed with saturated aqueous NaCl (100 mL), dried over $MgSO_4$, filtered and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (EtOAc/hexane = 1/100) to provide **5** as a white solid (3.60 g, 47% yield), m.p. = 88–90 °C; $[\alpha]_D^{20}$ = −23.8 (*c* = 1.00, THF). ^1H NMR (400 MHz, $CDCl_3$): δ 8.49 (s, 1H), 7.88 (dd, *J* = 8.2, 5.3 Hz, 2H), 7.77 (d, *J* = 8.2 Hz, 1H), 7.50 (d, *J* = 8.4 Hz, 1H), 7.40–7.35 (m, 2H), 7.24–7.20 (m, 2H), 7.13 (d, *J* = 8.4 Hz, 1H), 7.01 (d, *J* = 8.5 Hz, 1H), 3.30 (s, 3H), 2.12 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.8, 139.2, 135.3, 133.7, 133.2, 132.5, 132.1, 131.6, 128.8, 128.5, 128.3, 128.1, 127.1, 127.0, 126.4, 125.9, 125.8, 125.7, 125.1, 92.9, 60.7, 20.7. HRMS-ESI (*m*/*z*): M^+ calcd for $C_{22}H_{17}IO$ 424.0324, found 424.0317.

(*R*)-2-Methoxy-2′-methyl-3-(trifluoromethyl)-1,1′-binaphthalene (6). All flasks used in the reaction were heated under vacuum for 30 minutes and purged with argon for 10 minutes. To a solution of CuI (3.08 g, 16.0 mmol), HMPA (5.6 mL, 32.0 mmol) and **5** (3.45 g, 8.0 mmol) in dry DMF (60 mL) was added dropwise $FSO_2CF_2CO_2Me$ (3.10 g, 16.0 mmol) at room temperature, and the resulting mixture was stirred under an argon atmosphere for 8 h at 70 °C. The reaction mixture was then cooled to room temperature and diluted with CH_2Cl_2

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(200 mL). The solution was washed with saturated aqueous NaCl (3 × 50 mL), dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by silica gel chromatography (petroleum ether) to give product **6** (2.62 g, 71% yield) as a white solid, m.p. = 65–66 °C; $[\alpha]_D^{20}$ = −37.2 (*c* = 1.00, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.18 (s, 1H), 7.91–7.72 (m, 3H), 7.42 (d, *J* = 8.4 Hz, 1H), 7.40–7.27 (m, 2H), 7.25–7.11 (m, 2H), 7.07 (d, *J* = 8.5 Hz, 1H), 6.99 (d, *J* = 8.5 Hz, 1H), 3.16 (s, 3H), 2.06 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.8, 135.7, 135.4, 133.3, 132.2, 130.9, 129.4, 129.3, 129.2, 128.9, 128.7, 128.6, 128.2, 128.1 (q, ^3J = 5.7 Hz), 126.6, 126.0, 125.9, 125.6, 125.2, 125.0 (q, $^1J_{C–F}$ = 272.5 Hz), 123.7 (q, $^2J_{C–F}$ = 30.0 Hz), 61.3, 20.6. ^{19}F NMR ($CDCl_3$): δ −62.6. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{23}H_{18}F_3O$ 367.1310, found 367.1303.

(*R*)-2′-(Bromomethyl)-2-methoxy-3-(trifluoromethyl)-1,1′-binaphthalene (7). To a solution of **6** (293 mg, 0.8 mmol) and AIBN (15 mg, 0.1 mmol) in DCE (30 mL) was added dropwise a solution of NBS (156 mg, 0.9 mmol) in DCE (10 mL) with stirring at room temperature, and the resulting mixture was refluxed for 6 h. After the reaction was completed, the reaction mixture was cooled to room temperature and was concentrated *in vacuo* to afford **7** (214 mg, 71% yield); m.p. = 75–76 °C, $[\alpha]_D^{20}$ = −53.7 (*c* = 1.00, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (s, 1H), 8.01 (dd, *J* = 17.2, 8.4 Hz, 2H), 7.93 (d, *J* = 8.2 Hz, 1H), 7.78 (d, *J* = 8.6 Hz, 1H), 7.54–7.47 (m, 2H), 7.38–7.29 (m, 2H), 7.18 (d, *J* = 8.5 Hz, 1H), 7.07 (d, *J* = 8.5 Hz, 1H), 4.49–4.32 (m, 2H), 3.23 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.7, 133.3, 133.0, 131.7, 129.7, 129.5, 129.2, 128.9 (q, $^3J_{C–F}$ = 5.7 Hz), 128.8, 128.4, 128.0, 127.2, 126.7, 126.6, 126.3, 123.1 (d, $^1J_{C–F}$ = 272.2 Hz), 122.4 (q, $^2J_{C–F}$ = 31.1 Hz), 61.7, 32.5. ^{19}F NMR ($CDCl_3$): δ −61.5. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{23}H_{16}BrF_3ONa$ 467.0234, found 467.0229.

(R_a,*S*)-2-(1-((2′-Methoxy-3′-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl) methyl) pyrrolidin-2-yl) propan-2-ol (8). Compound **7** was added to a mixture of (*S*)-2-(pyrrolidin-2-yl)propan-2-ol (196 mg, 1.2 mmol), potassium carbonate (215 mg, 1.6 mmol) and NaI (15 mg, 0.1 mmol) in acetonitrile (20 mL). The mixture was stirred at room temperature for 16 h. Crude product was purified by silica gel chromatography (petroleum ether : ethyl acetate = 1 : 1) to give product **8** as a white powder (260 mg, 66% yield), m.p. = 99–101 °C; $[\alpha]_D^{20}$ = −158.0 (*c* = 1.25, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.16 (s, 1H), 7.86 (d, *J* = 8.5 Hz, 1H), 7.84–7.77 (m, 2H), 7.76 (d, *J* = 8.1 Hz, 1H), 7.34–7.23 (m, 2H), 7.16–7.05 (m, 2H), 7.01 (d, *J* = 8.5 Hz, 1H), 6.90 (d, *J* = 8.5 Hz, 1H), 3.73 (d, *J* = 14.1 Hz, 1H), 3.37 (d, *J* = 14.1 Hz, 1H), 3.06 (s, 3H), 2.71–2.58 (m, 1H), 2.45–2.32 (m, 1H), 2.24 (dd, *J* = 8.9, 5.0 Hz, 1H), 1.62–1.48 (m, 1H), 1.47–1.34 (m, 3H), 0.75 (s, 3H), 0.64 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.9, 138.0, 135.9, 133.4, 132.8, 130.7, 129.2, 129.1, 128.7, 128.5, 128.4 (q, ^3J = 5.8 Hz), 128.2, 127.5, 126.6, 126.1, 126.0, 125.8, 125.6, 123.84 (q, $^1J_{C–F}$ = 272.6 Hz), 123.82 (q, ^2J = 30.2 Hz), 73.3, 72.2, 61.3, 61.2, 55.3, 28.3, 27.7, 25.1, 25.0. ^{19}F NMR ($CDCl_3$): δ −61.6. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{30}H_{31}F_3NO_2$ 494.2307, found 494.2300.

(*R*)-3-Iodo-2′-methyl-[1,1′-binaphthalen]-2-ol (9). To a solution of **5** (3.80 g, 9.0 mmol) in 30 mL of DCM was added BBr_3 (36 mL, 36.0 mmol, 1 M in DCM) over a period of 1 h at 0 °C under argon. The reaction was monitored with TLC (petroleum ether). After the completion of the reaction, the mixture was poured into ice water, extracted with DCM (20 mL × 3). The combined organic layer was washed with saturated aqueous NaCl (50 mL), dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by silica gel chromatography (petroleum ether) to give product **9** (3.65 g, 99% yield) as a white solid, m.p. = 81–83 °C; $[\alpha]_D^{20}$ = +39.1 (*c* = 1.00, DCM). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.47 (s, 1H), 7.96–7.89 (m, 2H), 7.80–7.74 (m, 1H), 7.55 (d, *J* = 8.4 Hz, 1H), 7.47–7.41 (m, 1H), 7.37–7.32 (m, 1H), 7.32–7.27 (m, 1H), 7.25–7.21 (m, 1H), 7.15 (dd, *J* = 8.4, 1.0 Hz, 1H), 6.96–6.91 (m, 1H), 5.25 (s, 1H), 2.14 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.0, 139.1, 136.9, 133.4, 132.9, 132.6, 130.6, 129.4, 129.1, 129.0, 128.3, 127.4, 127.2, 127.1, 125.7, 125.3, 124.9, 124.4, 118.2, 86.0, 20.3. HRMS-ESI (*m*/*z*): M^+ calcd for $C_{21}H_{15}IO$ 410.0168, found 410.0175.

(*R*)-2-Methoxy-2′-methyl-3-phenyl-1,1′-binaphthalene (10). 1,3-Bis(diphenylphosphino)propane nickel(II) chloride (650 mg, 1.2 mmol) and iodide **5** (4.24 g, 10.0 mmol) were weighed into a 250 mL 3-neck flask and the flask was flushed with argon. Dry THF (100 mL) was added through a syringe. The mixture was cooled to 0 °C, and PhMgBr (3.0 M in THF, 14.0 mL, 40.0 mmol) was added dropwise. The reaction suspension was allowed to warm to room temperature in a period of 2 h and refluxed for an additional 12 h. It was then cooled to 0 °C and quenched by slow addition of 1 M HCl aqueous solutions. The organic layer was separated and the aqueous phase was extracted with AcOEt (50 mL × 3). The combined organic layer was washed with saturated aqueous NaCl (50 mL), dried over $MgSO_4$ and concentrated *in vacuo*. The crude product was purified by silica gel chromatography (petroleum ether) to give product **10** (3.21 g, 86% yield) as a white solid, m.p. = 90–92 °C; $[\alpha]_D^{20}$ = −16.9 (*c* = 1.00, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96 (s, 1H), 7.94–7.85 (m, 3H), 7.78–7.69 (m, 2H), 7.52 (d, *J* = 8.5 Hz, 1H), 7.47–7.36 (m, 5H), 7.31–7.20 (m, 3H), 7.09–7.03 (m, 1H), 3.02 (s, 3H), 2.21 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.6, 139.0, 135.3, 135.1, 133.5, 133.2, 132.6, 132.2, 131.1, 130.4, 129.5, 128.8, 128.4, 128.2, 128.1, 127.8, 127.4, 126.5, 126.2, 126.1, 125.6, 125.2, 124.9, 60.4, 20.8. HRMS-ESI (*m*/*z*): M^+ calcd for $C_{28}H_{22}O$ 374.1671, found 374.1664.

(*R*)-2′-Methyl-3-phenyl-[1,1′-binaphthalen]-2-ol (11). Compound **11** was prepared according to the procedure of **9** and was isolated as a white solid (2.93 g, 96% yield) after flash chromatography (petroleum ether), m.p. = 66–67 °C; $[\alpha]_D^{20}$ = +35.6 (*c* = 1.00, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.97 (s, 1H), 7.96–7.86 (m, 3H), 7.77–7.70 (m, 2H), 7.54 (d, *J* = 8.4 Hz, 1H), 7.47–7.24 (m, 7H), 7.22–7.18 (m, 1H), 6.96 (d, *J* = 8.4 Hz, 1H), 4.99 (s, 1H), 2.18 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.4, 138.1, 137.2, 133.3, 133.0, 132.7, 130.4, 130.1, 129.8, 129.32, 129.28, 129.1, 128.5, 128.4, 128.3, 127.7, 126.9, 126.8, 125.6, 124.6, 123.9, 118.6, 20.4. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{27}H_{20}ONa$ 383.1412, found 383.1406.

(*R*)-3-Iodo-2′-methyl-[1,1′-binaphthalen]-2-yl acetate (12a). To a solution of **9** (3.60 g, 8.0 mmol) in dry DCM (30 mL) was added acetic anhydride (1.64 g, 16.0 mmol) and pyridine

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(3.2 mL, 40.0 mmol) at room temperature. The mixture was stirred for 6 h until the starting material was consumed. The crude product was purified by silica gel chromatography (petroleum ether) to give product **12a** (3.56 g, 99% yield) as a white solid, m.p. = 96–97 °C; $[\alpha]_D^{20}$ = +7.6 (*c* = 1.20, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.52 (s, 1H), 7.89–7.80 (m, 3H), 7.49–7.37 (m, 3H), 7.32–7.22 (m, 2H), 7.16–7.05 (m, 2H), 2.08 (s, 3H), 1.73 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.1, 146.3, 139.1, 133.4, 133.1, 132.6, 132.0, 130.5, 130.1, 128.7, 128.5, 127.8, 127.5, 127.2, 126.7, 126.3, 126.2, 126.0, 125.2, 90.5, 20.6, 20.4. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{23}H_{17}IO_2Na$ 475.0171, found 475.0166.

(*R*)-2′-Methyl-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (12b). Compound **12b** was prepared according to the procedure of **6** and was isolated as a white solid (3.90 g, 78% yield) after flash chromatography (petroleum ether), m.p. = 73–75 °C; $[\alpha]_D^{20}$ = +72.3 (*c* = 1.30, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.35 (s, 1H), 8.04 (d, *J* = 8.2 Hz, 1H), 7.88 (t, *J* = 7.9 Hz, 2H), 7.61–7.53 (m, 1H), 7.47 (d, *J* = 8.4 Hz, 1H), 7.45–7.34 (m, 2H), 7.31–7.18 (m, 2H), 7.17–7.08 (m, 1H), 2.11 (s, 3H), 1.64 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.3, 143.0, 136.1, 134.8, 132.6, 132.0, 131.7, 130.6, 129.4, 129.3, 129.2, 128.8, 128.7, 128.2 (q, $^3J_{C-F}$ = 5.5 Hz), 127.9, 127.1, 126.4, 126.2, 125.3, 123.5 (q, $^1J_{C-F}$ = 273.5 Hz), 122.3 (q, $^2J_{C-F}$ = 32.4 Hz), 20.4, 20.0. ^{19}F NMR ($CDCl_3$): δ −61.5 HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{24}H_{17}F_3O_2Na$ 417.1078, found 417.1073.

(*R*)-2′-Methyl-3-phenyl-[1,1′-binaphthalen]-2-yl acetate (12c). Compound **12c** was prepared according to the procedure of **12a** and was isolated as a white solid (3.90 g, 78% yield) after flash chromatography (petroleum ether), m.p. = 80–82 °C; $[\alpha]_D^{20}$ = +21.7 (*c* = 0.50, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (s, 1H), 7.94 (d, *J* = 8.2 Hz, 1H), 7.85 (dd, *J* = 8.5, 1.9 Hz, 2H), 7.64–7.56 (m, 2H), 7.48–7.31 (m, 6H), 7.31–7.21 (m, 3H), 7.15 (d, *J* = 8.4 Hz, 1H), 2.15 (s, 3H), 1.39 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.6, 144.8, 138.2, 135.1, 133.0, 132.7, 132.2, 132.1, 131.1, 129.9, 129.4, 129.3, 128.7, 128.42, 128.38, 128.1, 127.8, 127.6, 126.9, 126.2, 125.9, 125.1, 20.5, 20.1. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{29}H_{22}O_2Na$ 425.1517, found 425.1518.

(*R*)-2′-(Bromomethyl)-3-iodo-[1,1′-binaphthalen]-2-yl acetate (13a). To a solution of **12a** (2.71 g, 6.0 mmol) and AIBN (100 mg, 0.6 mmol) in DCE (80 mL) was added dropwise a solution of NBS (1.19 g, 6.6 mmol) in DCE (30 mL) with stirring at room temperature, and the resulting mixture was refluxed for 6 h. After the reaction was completed, the reaction mixture was cooled to room temperature and was concentrated *in vacuo*. Purification was carried out by column chromatography (petroleum ether) to afford product **13a** as a white solid (1.85 g, 58% yield). m.p. = 97–99 °C, $[\alpha]_D^{20}$ = −12.6 (*c* = 0.60, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.56 (s, 1H), 7.97 (d, *J* = 8.6 Hz, 1H), 7.86 (dd, *J* = 13.1, 8.2 Hz, 2H), 7.72 (d, *J* = 8.6 Hz, 1H), 7.52–7.43 (m, 2H), 7.35–7.25 (m, 2H), 7.13 (t, *J* = 10.2 Hz, 2H), 4.38 (d, *J* = 10.6 Hz, 1H), 4.24 (d, *J* = 10.6 Hz, 1H), 1.77 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.3, 146.5, 139.8, 134.6, 133.3, 133.1, 132.2, 131.3, 129.6, 128.2, 128.0, 127.8, 127.5, 127.2, 127.1, 127.0, 126.9, 126.8, 90.2, 32.5, 20.7. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{23}H_{16}BrIO_2Na$ 552.9276, found 552.9276.

(*R*)-2′-(Bromomethyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (13b). Compound **13b** was prepared according to the procedure of **13a** and was isolated as a white solid (3.80 g, 64% yield) after flash chromatography (petroleum ether); m.p. = 81–83 °C, $[\alpha]_D^{20}$ = +3.3 (*c* = 0.70, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.40 (s, 1H), 8.07–8.02 (m, 1H), 8.00 (d, *J* = 8.5 Hz, 1H), 7.91–7.86 (m, 1H), 7.74 (d, *J* = 8.6 Hz, 1H), 7.59 (ddd, *J* = 8.2, 6.8, 1.2 Hz, 1H), 7.50–7.42 (m, 2H), 7.33–7.25 (m, 2H), 7.14–7.08 (m, 1H), 4.43 (d, *J* = 10.7 Hz, 1H), 4.22 (d, *J* = 10.7 Hz, 1H), 1.68 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.5, 143.1, 135.1, 134.8, 133.1, 132.2, 130.7, 130.6, 130.1, 130.0, 129.8, 129.2, 128.9 (q, $^3J_{C-F}$ = 5.5 Hz), 128.1, 127.8, 127.6, 127.5, 127.1, 127.0, 126.8, 123.2 (q, $^1J_{C-F}$ = 273.4 Hz), 122.3 (q, $^2J_{C-F}$ = 31.8 Hz), 32.6, 20.0. ^{19}F NMR ($CDCl_3$): δ −61.6. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{24}H_{16}BrF_3O_2Na$ 495.0183, found 495.0176.

(*R*)-2′-(Bromomethyl)-3-phenyl-[1,1′-binaphthalen]-2-yl acetate (13c). Compound **13c** was prepared according to the procedure of **13a** and was isolated as a white solid (1.36 g, 75% yield) after flash chromatography (petroleum ether); m.p. = 59–61 °C, $[\alpha]_D^{20}$ = +51.4 (*c* = 1.25, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.03 (s, 1H), 7.97–7.89 (m, 2H), 7.85 (d, *J* = 8.2 Hz, 1H), 7.72 (d, *J* = 8.6 Hz, 1H), 7.60 (d, *J* = 7.2 Hz, 2H), 7.47–7.38 (m, 4H), 7.36–7.22 (m, 4H), 4.61–4.10 (m, 2H), 1.40 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.7, 145.1, 137.9, 134.9, 134.6, 133.1, 132.7, 132.6, 132.1, 130.6, 129.3, 128.5, 128.4, 128.2, 127.9, 127.8, 127.4, 126.91, 126.85, 126.7, 126.5, 32.8, 20.2. HRMS-ESI (*m*/*z*): $[M + Na]^+$ calcd for $C_{29}H_{21}BrO_2Na$ 503.0623, found 503.0615.

(R_a,*S*)-2′-((2-(2-Hydroxypropan-2-yl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-yl acetate (14a). Compound **13a** (1.06 g, 2.0 mmol) was added to a mixture of (*S*)-2-(pyrrolidin-2-yl) propan-2-ol (500 mg, 3.0 mmol), potassium carbonate (544 mg, 4.0 mmol) and NaI (30 mg, 0.2 mmol) in acetonitrile (40 mL) with stirring at room temperature for 16 h. The organic layer was separated and the aqueous phase was extracted with AcOEt (30 mL × 3). The combined organic layer was dried over anhydrous Na_2SO_4, filtered and concentrated *in vacuo*. The crude product was purified by silica gel chromatography (petroleum ether : ethyl acetate = 1 : 1) to give product **14a** as a white powder (891 mg, 77% yield), m.p. = 101–102 °C; $[\alpha]_D^{20}$ = +11.8 (*c* = 0.60, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.45 (s, 1H), 7.90–7.68 (m, 4H), 7.40–7.28 (m, 2H), 7.20–7.12 (m, 2H), 7.07–7.01 (m, 1H), 6.96 (d, *J* = 8.5 Hz, 1H), 3.72 (d, *J* = 14.6 Hz, 1H), 3.38 (d, *J* = 14.5 Hz, 1H), 2.72 (dd, *J* = 7.7, 3.3 Hz, 1H), 2.39–2.23 (m, 2H), 1.94–1.75 (m, 1H), 1.65 (s, 3H), 1.58–1.45 (m, 3H), 0.84 (s, 3H), 0.77 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.9, 145.7, 139.3, 137.4, 133.6, 133.3, 132.6, 132.4, 130.4, 129.6, 128.7, 127.8, 127.32, 127.26, 126.8, 126.7, 126.4, 126.3, 125.7, 90.6, 73.3, 72.4, 60.9, 55.2, 28.3, 27.8, 25.2, 25.1, 20.7. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{30}H_{31}INO_3$ 580.1349, found 580.1346.

(R_a,*S*)-2′-((2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-yl acetate (14b). Compound **14b**

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was prepared according to the procedure of **14a** and was isolated as a white powder (633 mg, 70% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m.p. = 142–143 °C; $[\alpha]_D^{20}$ = +9.4 (*c* = 0.40, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.43 (s, 1H), 7.86 (d, *J* = 8.5 Hz, 1H), 7.82–7.70 (m, 3H), 7.39–7.28 (m, 2H), 7.18–7.10 (m, 2H), 7.03 (d, *J* = 8.6 Hz, 1H), 6.96 (d, *J* = 8.5 Hz, 1H), 3.64 (d, *J* = 14.2 Hz, 1H), 3.39 (d, *J* = 14.2 Hz, 1H), 2.69–2.50 (m, 1H), 2.51–2.34 (m, 2H), 1.69–1.51 (m, 5H), 1.50–1.41 (m, 2H), 1.33–1.24 (m, 1H), 1.11–0.92 (m, 2H), 0.79 (dd, *J* = 14.4, 7.7 Hz, 1H), 0.59 (t, *J* = 7.6 Hz, 3H), 0.52 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.8, 145.8, 139.4, 137.3, 133.7, 133.2, 132.6, 132.4, 130.7, 129.5, 128.6, 127.7, 127.2, 127.1, 126.7, 126.5, 126.4, 126.3, 125.7, 90.4, 75.6, 70.3, 60.9, 54.6, 28.9, 27.2, 25.8, 24.9, 20.6, 8.1, 7.8. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{32}H_{35}INO_3$ 608.1662, found 608.1657.

(R_a,*S*)-2′-((2-(Hydroxydiphenylmethyl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-yl acetate (14c). Compound **14c** was prepared according to the procedure of **14a** and was isolated as a white powder (420 mg, 59% yield) after flash chromatography (petroleum ether : ethyl acetate = 4 : 1), m.p. = 98–100 °C; $[\alpha]_D^{20}$ = +6.1 (*c* = 0.70, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.50 (s, 1H), 7.96–7.74 (m, 4H), 7.47–7.33 (m, 6H), 7.22–6.93 (m, 9H), 6.47 (s, 1H), 4.66 (s, 1H), 3.77–3.58 (m, 1H), 3.12–2.77 (m, 3H), 2.37–2.21 (m, 1H), 1.81 (d, *J* = 8.5 Hz, 1H), 1.69–1.59 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.9, 147.5, 146.5, 145.4, 139.3, 136.7, 133.2, 133.0, 132.4, 132.2, 129.0, 128.6, 128.1, 128.0, 127.7, 127.0, 126.5, 126.3, 126.2, 126.0, 125.6, 125.3, 90.4, 78.0, 71.0, 57.9, 55.1, 29.7, 24.5, 20.6. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{40}H_{35}INO_3$ 704.1662, found 704.1667.

(R_a,*S*)-2′-((2-(2-Hydroxypropan-2-yl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (14d). Compound **14d** was prepared according to the procedure of **14a** and was isolated as a white powder (680 mg, 61% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m.p. = 103–105 °C; $[\alpha]_D^{20}$ = +5.8 (*c* = 0.45, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.27 (s, 1H), 7.98–7.80 (m, 3H), 7.78 (d, *J* = 8.2 Hz, 1H), 7.47–7.43 (m, 1H), 7.34–7.25 (m, 2H), 7.18–7.11 (m, 1H), 7.06–7.03 (m, 2H), 3.73 (d, *J* = 14.6 Hz, 1H), 3.41 (d, *J* = 14.6 Hz, 1H), 2.72 (dt, *J* = 11.4, 5.4 Hz, 1H), 2.45–2.25 (m, 2H), 1.67–1.42 (m, 7H), 0.82 (s, 3H), 0.73 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.1, 142.4, 137.8, 135.3, 132.7, 132.5, 131.3, 130.6, 129.4, 129.3, 129.0, 128.5 (q, $^3J_{C-F}$ = 5.4 Hz), 127.8, 127.2, 126.7, 126.5, 126.4, 126.3, 125.8, 123.3 (q, $^1J_{C-F}$ = 272.8 Hz), 122.6 (q, $^2J_{C-F}$ = 31.3 Hz), 73.4, 72.4, 61.0, 55.2, 28.3, 27.8, 25.1, 19.9. ^{19}F NMR ($CDCl_3$): δ −62.3. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{31}H_{31}F_3NO_3$ 522.2256, found 522.2249.

(R_a,*S*)-2′-((2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (14e). Compound **14e** was prepared according to the procedure of **14a** and was isolated as a white powder (440 mg, 79% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m.p. = 101–102 °C; $[\alpha]_D^{20}$ = +11.1 (*c* = 0.90, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.28 (s, 1H), 7.95 (d, *J* = 8.2 Hz, 1H), 7.90 (d, *J* = 8.5 Hz, 1H), 7.84–7.71 (m, 2H), 7.53–7.43 (m, 1H), 7.38–7.25 (m, 2H), 7.19–7.13 (m, 1H), 7.12–6.95 (m, 2H), 3.64 (d, *J* = 14.3 Hz, 1H), 3.43 (d, *J* = 14.2 Hz, 1H), 2.66–2.52 (m, 1H), 2.52–2.29 (m, 2H), 1.62–1.37 (m, 7H), 1.28 (dd, *J* = 14.3, 7.4 Hz, 1H), 1.12–0.90 (m, 2H), 0.82–0.73 (m, 1H), 0.60 (t, *J* = 7.6 Hz, 3H), 0.49 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.1, 142.4, 139.4, 137.8, 135.4, 132.7, 132.5, 131.3, 130.6, 129.6, 129.4, 128.9, 128.56 (q, $^3J_{C-F}$ = 5.3 Hz), 127.3, 127.2, 126.4, 126.4, 125.9, 123.35 (q, $^1J_{C-F}$ = 272.7 Hz), 122.54 (q, $^2J_{C-F}$ = 31.4 Hz), 75.7, 70.4, 61.1, 54.7, 28.9, 27.3, 25.8, 25.0, 19.9, 8.0, 7.8. ^{19}F NMR ($CDCl_3$): δ −62.6. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{33}H_{35}F_3NO_3$ 550.2569, found 550.2580.

(R_a,*S*)-2′-((2-(Hydroxydiphenylmethyl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (14f). Compound **14f** was prepared according to the procedure of **14a** and was isolated as a white powder (1.10 g, 72% yield) after flash chromatography (petroleum ether : ethyl acetate = 4 : 1), m.p. = 99–101 °C; $[\alpha]_D^{20}$ = +12.6 (*c* = 0.50, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.25 (s, 1H), 7.88 (dd, *J* = 14.2, 8.4 Hz, 2H), 7.82–7.68 (m, 2H), 7.48–7.40 (m, 1H), 7.37–7.24 (m, 5H), 7.15–7.08 (m, 4H), 7.05–6.97 (m, 1H), 6.94–6.81 (m, 4H), 6.46 (d, *J* = 8.5 Hz, 1H), 4.66 (s, 1H), 3.62 (dd, *J* = 9.1, 4.2 Hz, 1H), 3.09–2.89 (m, 2H), 2.78 (d, *J* = 15.1 Hz, 1H), 2.43–2.27 (m, 1H), 1.81–1.66 (m, 1H), 1.65–1.52 (m, 3H), 1.49 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.2, 147.6, 146.5, 142.1, 137.2, 134.9, 132.5, 132.2, 130.7, 130.4, 129.6, 129.2, 128.9, 128.4 (q, $^3J_{C-F}$ = 5.5 Hz), 128.3, 128.1, 128.0, 127.8, 127.0, 126.3, 126.2, 126.1, 126.0, 125.8, 125.7, 125.4, 125.2, 123.3 (q, $^1J_{C-F}$ = 272.8 Hz), 122.3 (q, $^2J_{C-F}$ = 31.4 Hz), 78.1, 71.3, 58.0, 55.2, 29.8, 24.6, 19.9. ^{19}F NMR ($CDCl_3$): δ −62.5. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{41}H_{35}F_3NO_3$ 646.2569, found 646.2555.

(R_a,*S*)-2′-((2-(2-Hydroxypropan-2-yl) pyrrolidin-1-yl) methyl)-3-phenyl-[1,1′-binaphthalen]-2-yl acetate (14g). Compound **14g** was prepared according to the procedure of **14a** and was isolated as a white powder (329 mg, 82% yield) after flash chromatography (petroleum ether : ethyl acetate = 4 : 1), m.p. = 125–127 °C; $[\alpha]_D^{20}$ = +19.1 (*c* = 0.90, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.05 (s, 1H), 8.03–7.83 (m, 4H), 7.66–7.57 (m, 2H), 7.52–7.36 (m, 5H), 7.31–7.25 (m, 3H), 7.13 (d, *J* = 8.5 Hz, 1H), 3.97 (d, *J* = 14.2 Hz, 1H), 3.58 (d, *J* = 14.2 Hz, 1H), 2.85 (dt, *J* = 11.0, 5.7 Hz, 1H), 2.65–2.41 (m, 2H), 2.02 (s, 1H), 1.79–1.56 (m, 4H), 1.42 (s, 3H), 0.95 (s, 3H), 0.93 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.2, 144.2, 138.2, 137.4, 135.2, 133.3, 132.8, 132.7, 132.0, 131.2, 130.1, 129.2, 128.8, 128.4, 128.4, 128.3, 127.7, 127.6, 127.0, 126.7, 126.5, 126.3, 126.2, 125.6, 73.3, 72.4, 61.1, 55.1, 28.4, 27.8, 25.1, 25.1, 20.1. HRMS-ESI (*m*/*z*): $[M + H]^+$ calcd for $C_{36}H_{36}NO_3$ 530.2695, found 530.2701.

(R_a,*R*)-2′-((2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-yl acetate (14h). Compound **14h** was prepared according to the procedure of **14a** and was isolated as a white powder (209 mg, 48% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m.p. = 110–112 °C; $[\alpha]_D^{20}$ = +43.7 (*c* = 1.10, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.66 (s, 1H), 8.41 (s, 1H), 8.04 (dd, *J* = 12.6, 8.4 Hz, 2H), 7.92 (d, *J* = 8.2 Hz, 1H), 7.66–7.57 (m, 1H), 7.55–7.43 (m, 2H), 7.28 (d, *J* = 14.3 Hz, 2H), 7.25–7.17 (m, 2H), 4.79 (d, *J* = 13.6 Hz, 1H), 4.07 (d, *J* = 13.6 Hz, 1H), 3.80–3.22

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(m, 2H), 3.21–2.91 (m, 1H), 2.48–2.28 (m, 1H), 2.23–2.02 (m, 1H), 1.75–1.46 (m, 7H), 1.44–1.35 (m, 1H), 1.24–1.09 (m, 1H), 0.69 (t, J = 7.5 Hz, 3H), 0.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.6, 135.1, 133.4, 132.0, 130.5, 130.4, 130.3, 129.8, 129.4, 129.2 (q, $^3J_{C-F}$ = 5.1 Hz), 129.1, 128.0, 127.7, 127.0, 126.7, 126.6, 123.2 (q, $^1J_{C-F}$ = 272.8 Hz), 122.3 (q, $^2J_{C-F}$ = 31.8 Hz), 75.8, 70.1, 28.8, 28.6, 24.9, 21.3, 20.1, 7.8, 7.2. ^{19}F NMR ($CDCl_3$): δ −62.7. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{33}H_{35}F_3NO_3$ 550.2569, found 550.2580.

(R_a,*S*)-2′-(((*S*)-2-(2-Hydroxypropan-2-yl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-ol (3a). Compound **14a** (580 mg; 1.0 mmol) and NaOH (88 mg; 2.2 mmol) were dissolved in methanol (20 mL) and the mixture was refluxed for 3 h to give product **3a** as a white powder (483 mg, 90% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m.p. = 110–112 °C, $[\alpha]_D^{20}$ = +28.3 (c = 0.80, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.51 (s, 1H), 8.37 (d, J = 8.6 Hz, 1H), 8.04 (d, J = 8.5 Hz, 1H), 7.89 (d, J = 8.2 Hz, 1H), 7.79 (dd, J = 8.4, 1.2 Hz, 1H), 7.50 (ddd, J = 8.1, 6.8, 1.2 Hz, 1H), 7.37–7.27 (m, 2H), 7.25–7.18 (m, 2H), 6.85–6.79 (m, 1H), 4.10 (t, J = 8.4 Hz, 2H), 3.42 (d, J = 12.8 Hz, 1H), 3.25–3.06 (m, 1H), 2.91 (d, J = 7.1 Hz, 1H), 1.92–1.70 (m, 2H), 1.26–1.15 (m, 2H), 1.13 (s, 3H), 0.77 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.5, 140.0, 134.3, 134.2, 133.7, 132.4, 130.3, 130.2, 129.6, 128.7, 128.5, 128.0, 127.6, 127.32, 127.27, 126.6, 124.7, 124.5, 116.8, 88.8, 70.1, 58.6, 55.4, 28.3, 26.3, 26.0, 23.3. IR (KBr): ν = 3420, 3055, 2939, 1728, 1197, 820 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{28}H_{29}INO_2$ 538.1243, found 538.1241.

(R_a,*S*)-2′-((2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-ol (3b). Compound **3b** was prepared according to the procedure of **3a** and was isolated as a white powder (349 mg, 83% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m p = 122–123 °C, $[\alpha]_D^{20}$ = +10.1 (c = 0.86, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.48 (s, 1H), 7.98 (d, J = 8.4 Hz, 1H), 7.92 (d, J = 8.2 Hz, 1H), 7.73 (dd, J = 11.9, 8.4 Hz, 2H), 7.46 (ddd, J = 8.1, 6.7, 1.3 Hz, 1H), 7.28–7.23 (m, 3H), 7.19–7.12 (m, 2H), 6.76 (dd, J = 8.4, 1.1 Hz, 1H), 3.80 (d, J = 13.1 Hz, 1H), 3.59 (d, J = 13.2 Hz, 1H), 3.03–2.88 (m, 2H), 2.50 (dd, J = 11.1, 5.9 Hz, 1H), 1.92–1.62 (m, 5H), 1.58–1.49 (m, 1H), 1.31–1.20 (m, 2H), 1.15 (dt, J = 14.8, 7.3 Hz, 1H), 1.09–1.00 (m, 1H), 0.74 (t, J = 7.5 Hz, 3H), 0.65 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.3, 139.0, 135.5, 134.3, 133.5, 133.1, 129.8, 128.6, 128.1, 127.8, 127.0, 126.8, 126.6, 126.5, 126.2, 124.8, 123.4, 118.7, 75.6, 71.3, 62.9, 56.2, 28.3, 26.8, 26.1, 24.6, 7.8, 7.6. IR (KBr): ν = 3477, 3056, 2937, 1736, 1188, 823 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{30}H_{33}INO_2$ 566.1556, found 566.1555.

(R_a,*S*)-2′-((2-(Hydroxydiphenylmethyl) pyrrolidin-1-yl) methyl)-3-iodo-[1,1′-binaphthalen]-2-ol (3c). Compound **3c** was prepared according to the procedure of **3a** and was isolated as a white powder (290 mg, 87% yield) after flash chromatography (petroleum ether : ethyl acetate = 2 : 1), m p = 112–114 °C, $[\alpha]_D^{20}$ = +34.7 (c = 1.00, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.48 (s, 1H), 7.95 (d, J = 8.6 Hz, 1H), 7.91–7.83 (m, 1H), 7.74 (dd, J = 18.1, 8.4 Hz, 2H), 7.43 (ddd, J = 7.3, 5.5, 1.7 Hz, 5H), 7.31 (t, J = 7.5 Hz, 1H), 7.23–7.16 (m, 3H), 7.14–7.02 (m, 5H), 6.98 (t, J = 7.2 Hz, 1H), 6.49 (d, J = 8.5 Hz, 1H), 3.67 (dd, J = 9.4, 4.4 Hz, 1H), 2.98–2.83 (m, 3H), 2.21–2.05 (m, 1H), 1.84–1.72 (m, 1H), 1.67–1.52 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.8, 136.7, 134.3, 133.3, 132.5, 131.0, 130.8, 130.0, 129.4, 129.3, 129.2, 129.1, 128.8, 128.7, 128.6, 127.8, 127.54, 127.48, 126.6, 124.6, 124.1, 116.8, 77.4, 70.3, 58.7, 55.0, 28.5, 26.8, 26.3, 23.4. IR (KBr): ν = 3378, 3054, 2974, 1736, 1201, 824 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{38}H_{33}INO_2$ 662.1556, found 662.1555.

(R_a,*S*)-2′-(((*S*)-2-(Hydroxydiphenylmethyl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-ol (3d). Compound **3d** was prepared according to the procedure of **3a** and was isolated as a white powder (590 mg, 94% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m p = 119–120 °C, $[\alpha]_D^{20}$ = −11.3 (c = 1.10, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.18 (s, 1H), 7.90 (dd, J = 8.6, 3.1 Hz, 1H), 7.82 (dd, J = 8.2, 3.7 Hz, 2H), 7.58 (dd, J = 8.5, 3.2 Hz, 1H), 7.41–7.30 (m, 1H), 7.21 (d, J = 7.6 Hz, 1H), 7.17–7.05 (m, 3H), 6.65 (dd, J = 8.7, 3.0 Hz, 1H), 3.76 (dd, J = 12.8, 3.3 Hz, 1H), 3.58 (dd, J = 12.8, 3.2 Hz, 1H), 3.05–2.94 (m, 2H), 2.49–2.43 (m, 1H), 2.00–1.90 (m, 1H), 1.76–1.74 (m, 3H), 0.97 (s, 3H), 0.82 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 153.1, 136.0, 134.9, 134.3, 133.8, 133.5, 129.2, 128.7, δ 128.4 (q, $^3J_{C-F}$ = 5.4 Hz), 128.3, 128.2, 128.1, 127.0, 126.9, 126.6, 126.4, 124.8, 123.6, 124.4 (d, $^1J_{C-F}$ = 272.4 Hz), 122.3 (q, $^2J_{C-F}$ = 29.2 Hz), 122.2, 74.7, 72.3, 63.5, 56.9, 27.9, 27.5, 24.8, 24.6. ^{19}F NMR ($CDCl_3$): δ −62.7. IR (KBr): ν = 3381, 3059, 2972, 1728, 1206, 823 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{29}H_{29}F_3NO_2$ 480.2150, found 480.2148.

(R_a,*S*)-2′-(((*S*)-2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-ol (3e). Compound **3e** was prepared according to the procedure of **3a** and was isolated as a white powder (360 mg, 95% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m p = 116–117 °C, $[\alpha]_D^{20}$ = +21.5 (c = 0.80, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.16 (s, 1H), 7.92 (d, J = 8.4 Hz, 1H), 7.88–7.81 (m, 2H), 7.61 (d, J = 8.4 Hz, 1H), 7.43–7.34 (m, 1H), 7.25–7.08 (m, 4H), 6.69 (d, J = 8.4 Hz, 1H), 3.74 (d, J = 12.9 Hz, 1H), 3.55 (d, J = 12.9 Hz, 1H), 3.04 (dd, J = 8.5, 5.8 Hz, 1H), 2.96–2.77 (m, 1H), 2.52–2.37 (m, 1H), 1.90–1.78 (m, 1H), 1.78–1.60 (m, 3H), 1.50–1.41 (m, 1H), 1.17–1.05 (m, 2H), 1.02–0.93 (m, 1H), 0.66 (t, J = 7.5 Hz, 3H), 0.56 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.2, 136.0, 135.5, 133.8, 133.4, 133.1, 129.3, 128.9, 128.5 (q, $^3J_{C-F}$ = 5.5 Hz), 128.3, 128.2, 127.1, 126.7, 126.6, 126.5, 125.5 (q, $^1J_{C-F}$ = 271.9 Hz), 124.8, 123.8, 122.0, 121.53 (q, $^2J_{C-F}$ = 29.6 Hz), 121.5, 75.6, 71.6, 63.2, 56.6, 28.3, 26.8, 26.3, 24.6, 7.9, 7.6. ^{19}F NMR ($CDCl_3$): δ −62.7. IR (KBr): ν = 3518, 3057, 2945, 1727, 1203, 819 cm^{-1}. HRMS-ESI (m/z): $[M + H]^+$ calcd for $C_{31}H_{33}F_3NO_2$ 508.2463, found 508.2461.

(R_a,*S*)-2′-(((*S*)-2-(Hydroxydiphenylmethyl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-ol (3f). Compound **3f** was prepared according to the procedure of **3a** and was isolated as a white powder (890 mg, 93% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m p = 121–122 °C, $[\alpha]_D^{20}$ = +89.1 (c = 0.44, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.19 (s, 1H), 7.91 (d, J = 8.6 Hz, 1H), 7.83 (dd, J = 12.7, 8.2 Hz, 2H), 7.67 (d, J = 8.7 Hz, 1H), 7.38–7.26 (m, 6H),

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7.17–7.08 (m, 4H), 7.03–6.87 (m, 5H), 6.43 (d, J = 8.5 Hz, 1H), 3.60 (dd, J = 9.6, 4.1 Hz, 1H), 2.94–2.71 (m, 3H), 2.07–2.01 (m, 1H), 1.79–1.66 (m, 1H), 1.61–1.43 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.6, 147.1, 146.4, 139.2, 135.4, 133.2, 132.4, 129.9, 129.1, 128.5, 128.4, 128.2, 128.1, 127.5, 127.3, 126.7, 126.6, 126.5, 126.4, 125.6, 125.4, 125.2, 125.1, 124.8, 124.5, 123.8 (q, $^1J_{C-F}$ = 272.5 Hz), 119.3, 118.4 (q, $^2J_{C-F}$ = 31.2 Hz), 78.2, 71.0, 58.2, 55.9, 29.4, 24.3. ^{19}F NMR ($CDCl_3$): δ −62.3. IR (KBr): ν = 3325, 3052, 2974, 1735, 1205, 815 cm^{-1}. HRMS-ESI (m/z): [M + H]$^+$ calcd for $C_{39}H_{33}F_3NO_2$ 604.2463, found 604.2459.

(R_a,*S*)-2′-((2-(2-Hydroxypropan-2-yl) pyrrolidin-1-yl) methyl)-3-phenyl-[1,1′-binaphthalen]-2-ol (3g). Compound **3g** was prepared according to the procedure of **3a** and was isolated as a white powder (290 mg, 88% yield) after flash chromatography (petroleum ether : ethyl acetate = 2 : 1), m p = 140–141 °C, $[\alpha]_D^{20}$ = +49.3 (c = 0.50, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.47 (d, J = 8.5 Hz, 1H), 8.11 (d, J = 8.1 Hz, 1H), 8.01 (s, 1H), 7.95 (dd, J = 11.1, 8.2 Hz, 2H), 7.63 (d, J = 6.9 Hz, 2H), 7.57–7.51 (m, 3H), 7.46 (t, J = 7.3 Hz, 1H), 7.43–7.35 (m, 3H), 7.30–7.25 (m, 2H), 6.90 (d, J = 8.4 Hz, 1H), 4.24 (d, J = 12.5 Hz, 1H), 4.05 (d, J = 12.7 Hz, 1H), δ 3.39 (d, J = 18.7 Hz, 1H), 3.13–2.96 (m, 2H), 1.92–1.80 (m, 2H), 1.29 (d, J = 13.1 Hz, 5H), 0.96 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.8, 136.7, 134.3, 133.3, 132.5, 131.0, 130.8, 130.0, 129.4, 129.3, 129.2, 129.1, 128.8, 128.7, 128.6, 127.8, 127.5, 127.5, 126.6, 124.6, 124.1, 116.8, 77.4, 70.3, 58.7, 55.0, 28.5, 26.8, 26.3, 23.4. IR (KBr): ν = 3377, 3054, 2972, 1731, 1196, 821 cm^{-1}. HRMS-ESI (m/z): [M + H]$^+$ calcd for $C_{34}H_{34}NO_2$ 488.2590, found 488.2588.

(R_a,*R*)-2′-((2-(3-Hydroxypentan-3-yl) pyrrolidin-1-yl) methyl)-3-(trifluoromethyl)-[1,1′-binaphthalen]-2-ol (3h). Compound **3h** was prepared according to the procedure of **3a** and was isolated as a white powder (190 mg, 81% yield) after flash chromatography (petroleum ether : ethyl acetate = 1 : 1), m p = 136–138 °C, $[\alpha]_D^{20}$ = +61.1 (c = 0.50, DCM). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.28 (s, 1H), 8.00 (d, J = 8.5 Hz, 1H), 7.95–7.85 (m, 3H), 7.53–7.44 (m, 1H), 7.38–7.30 (m, 1H), 7.26–7.17 (m, 2H), 7.08 (dd, J = 8.6, 1.1 Hz, 1H), 6.64 (dd, J = 8.5, 1.1 Hz, 1H), 4.73 (d, J = 12.3 Hz, 1H), 4.11–4.00 (m, 2H), 3.70–3.57 (m, 1H), 3.23 (s, 1H), 2.27–2.16 (m, 1H), 2.10–2.06 (m, 1H), 2.03–1.96 (m, 1H), 1.75–1.52 (m, 3H), 1.42–1.32 (m, 1H), 1.28–1.23 (m, 1H), 0.97 (t, J = 7.4 Hz, 3H), 0.82 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.1, 136.9, 136.2, 134.3, 133.0, 129.3, 128.8 (q, $^3J_{C-F}$ = 4.9 Hz), 128.7, 128.6, 128.3, 128.2, 127.1, 126.9, 126.8, 124.6, 124.1, 124.09 ($^1J_{C-F}$ = 273.6 Hz), 121.7 (q, $^3J_{C-F}$ = 30.1 Hz), 120.3, 80.3, 75.9, 74.4, 72.8, 29.0, 27.4, 24.8, 21.3, 7.9, 7.3. ^{19}F NMR ($CDCl_3$): δ −62.6. IR (KBr): ν = 3516, 3056, 2941, 1725, 1203, 818 cm^{-1}. HRMS-ESI (m/z): [M + H]$^+$ calcd for $C_{31}H_{33}F_3NO_2$ 508.2463, found 508.2461.

4.3. General procedure for enantioselective arylation of aromatic aldehydes

Under an argon atmosphere, Et_2Zn (7.2 equiv., 1.8 mmol, 1.8 mL, 1.0 M in toluene) was added slowly to a solution of arylboronic acid (2.4 equiv., 0.6 mmol) in dry toluene (2 mL) and the latter was heated at 60 °C for 12 h. After the mixture was cooled to 0 °C, a solution of chiral ligand **3f** (14 mg, 10 mol%) and DiMPEG 2000 (50 mg, 10 mol%) in 1 mL dry toluene was added through a syringe. The reaction mixture was stirred for 30 min followed by the addition of the aldehyde (0.25 mmol). After reacting at 0 °C for 24 h (36 h for arylation–lactonization reaction), the reaction mixture was carefully quenched by the addition of 1 M HCl. The mixture was extracted with ethyl acetate (10 mL × 3). The combined organic layers were washed with brine, dried over anhydrous $MgSO_4$ and concentrated *in vacuo*, and were purified using flash chromatography to afford the product. The enantiomeric excess of the product was determined by HPLC analysis.

Conflicts of interest

The authors declare no competing financial interest.

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18 We also tried the recovery of the chiral ligand. Indeed, the chiral ligand **3f** could be recovered and reused. However, due to the low catalyst loading and the polar nature of the compound, the recovered yield was not so satisfactory (*ca.* 50%). The recovery experiments were not pursued further.

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