A General and Direct Reductive Amination of Aldehydes and Ketones with Electron-Deficient Anilines

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In memoriam Philipp Köck

Abstract In our ongoing efforts in preparing tool compounds for investigating and controlling the biosynthesis of phenazines, we recognized the limitations of existing protocols for C–N bond formation of electron-deficient anilines when using reductive amination. After extensive optimization, we have established three robust and scalable protocols for the reductive amination of ketones with electron-deficient anilines, by using either BH$_3$·THF/AcOH/CH$_2$Cl$_2$ (method A), with reaction times of several hours, or the more powerful combinations BH$_3$·THF/TMSCl/DMF (method B) and NaBH$_4$/TMSCl/DMF (method C), which give full conversions for most substrates within 10 to 25 minutes. The scope and limitations of these reactions have been defined for 12 anilines and 14 ketones.

Key words amines, anilines, borane, hydride, reductive amination, ketones, process chemistry, sodium borohydride

Introduction

In 2005 I saw at a conference in London a poster by the structural biologist and enzymologist Wulf Blankenfeldt, who presented his progress on the investigation of the biosynthesis of phenazines, a class of bacterial natural products among which the virulence factor pyocyanine is probably its most prominent member. He had already solved the structure of several enzymes along this biosynthetic pathway, but there were several open mechanistic questions, for which it would be important to have substrate analogues binding to these proteins. These probes would ideally serve also as inhibitors of these enzymes, potentially allowing the chemical control of the biosynthesis pathway – an attractive goal and formidable challenge for a synthetic organic chemist and the starting point of a fruitful collaboration between our two groups.
(ITC) and X-ray crystallography of the protein ligand complex, to bind to PhzA/B. This work was continued by Matthias Mentel, who, after the move of our laboratory to the University of Leipzig, used information gained from X-ray crystallography and ITC to design even more potent molecules, ultimately leading to two important ligands, which we named ‘Phenazistatin’ (F) and ‘Maverick’ (G) (Figure 1). Phenazistatin, which binds to PhzA/B with a $K_d = 51$ nM, is a strongly affine ligand, mimicking the intermediate after the first imine formation catalyzed by PhzA/B. The X-ray crystal structure of the protein–ligand complex of PhzA/B·F proved important for the unambiguous assignment of the biological purpose and mechanistic details of PhzA/B function.2

Compound G was isolated in 1% yield, as Matthias noticed it as a minor byproduct in the Ullmann–Goldberg reaction of 2-bromobenzoic acid with 3-aminopiperidine, where waste products of the Ullmann–Goldberg reaction led to racemic G by bromination of the main product. When subjecting it to ITC and X-ray crystal structure analysis, we made the completely unexpected and stunning observation that for racemic G both enantiomers were found in the binding pocket of PhzA/B simultaneously. We have carefully investigated this case, which is the first example in which the textbook notion of eutomer vs. distomer behavior of racemic drugs is not valid, since each enantiomer of Maverick (G) binds more strongly to the protein than its racemate.3

After the move of our laboratory to Graz, Jakob Pletz continued the work of Matthias Mentel, and tried to prepare even more affine ligands of PhzA/B and analogues of Maverick, exploring if other molecules would also exhibit the amazing phenotype of simultaneous binding of racemic

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Biographical sketches

**Jakob Pletz** was born in Oberpullendorf (Austria) in 1987. He obtained his B.Sc. in chemistry and his M.Sc. in technical chemistry from the Graz University of Technology and the University of Graz. After an Erasmus exchange stay in the laboratory of Professor John K. Gallos at the Aristotle University of Thessaloniki (Greece), he carried out his Diploma thesis project under the guidance of Professor Rolf Breinbauer. Since 2012 he has been working on his Ph.D. thesis on the synthesis and biological characterization of analogues of amine-containing natural products under the guidance of Professor Rolf Breinbauer at the Graz University of Technology (Austria).

**Bernhard Berg** was born in San Francisco (USA) in 1990. He finished his primary education (elementary and high school) in Linz (Austria) and began studying chemistry at the Graz University of Technology in 2011, accomplishing his B.Sc. thesis under the supervision of Prof. Rolf Breinbauer in early 2015. In the summer 2015 he worked in the laboratory of Nancy I. Totah, in the Department of Chemistry at Syracuse University (USA). Since 2015 he has been pursuing his Master studies in technical chemistry at the Graz University of Technology (Austria).

**Rolf Breinbauer** was born in Schärding (Austria) in 1970. He studied chemistry at the Vienna University of Technology and the University of Heidelberg, carrying out his Diploma thesis project under the guidance of Professor Günter Helmchen. From 1995 to 1998, he worked as a Ph.D. student under the guidance of Professor Manfred T. Reetz at the Max-Planck-Institut für Kohlenforschung in Mülheim/Ruhr (Germany). After working as a postdoctoral researcher with an Erwin-Schrödinger fellowship in the laboratory of Professor Eric N. Jacobsen (Harvard University, USA), he moved in 2000 to Dortmund (Germany) as a group leader at the Max-Planck Institute of Molecular Physiology (department head: Professor Herbert Waldmann) and as a junior professor at the University of Dortmund. From 2005 to 2007 he was a professor of organic chemistry at the University of Leipzig. Since 2007, he has been a full professor of organic chemistry at the Graz University of Technology in Graz (Austria). His research interests encompass the design and synthesis of tool compounds for chemical biology and the development of new synthetic methods.
molecules in a single binding pocket. Jakob soon recognized that a major limitation in his work was the inefficiency of the Ullmann–Goldberg reaction for the C–N bond formation.4 Despite considerable efforts and some success in improving the yields for some substrates by optimizing the reaction conditions, no reliable protocol could be found which was suitable for the diverse and highly functionalized substrates of our ligands. Jakob suggested a different route in which the C–N bond is formed with the alkyl carbon by using reductive amination as the strategic transformation, which should lead to higher yields and have the additional advantage that the required ketone substrates are more available than the alicyclic amines necessary for the Ullmann–Goldberg route (Figure 2). The lack of control of the resulting stereogenic center should not bother us at this early stage of biological testing with PhzA/B, because we have learned from the studies with Maverick (G) that racemic ligands could offer interesting surprises with this particular protein. First we had to develop more efficient protocols for reductive aminations, as we soon noticed that all established protocols proved to be inefficient for our electron-deficient aniline substrates. In this article we want to report three methods, which proved to be very valuable for this type of substrates.

**Figure 1** Structures of Phenazistatin (F) and Maverick (G)

**Figure 2** Strategic disconnections for the synthesis of PhzA ligands

**Table 1** Screening of Reductive Amination Methods

<table>
<thead>
<tr>
<th>Entry</th>
<th>Conditions</th>
<th>Ref.</th>
<th>Product formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1. toluene, 4 Å MS, reflux, Dean–Stark, 4 d 2. NaBH₄ (3 equiv), MeOH, N₂, 20 °C, 6 h</td>
<td>14</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>1. PTSA, toluene, reflux, Dean–Stark, 2 d 2. NaBH₄ (3 equiv), MeOH, N₂, 20 °C, 6 h</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>TiCl₄ (0.5 equiv), Et₃N (2.0 equiv), CH₂Cl₂, 20 °C, 4 d</td>
<td>15</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>1. Ti(ÔPr)₄, neat, 20 °C, 1 h 2. NaCNBH₃ (0.55 equiv), EtOH, 20 °C, 3 d</td>
<td>16</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>1. Ti(ÔPr)₄ (1.25 equiv), neat, 40 °C, 16 h 2. NaBH₄ (2 equiv), 0–20 °C, EtOH, 6 h</td>
<td>17</td>
<td>–</td>
</tr>
<tr>
<td>6</td>
<td>1. Ti(ÔPr)₄ (1.25 equiv), neat, 40 °C, 16 h 2. PMHS (2 equiv), 0–20 °C, THF, 6 h</td>
<td>18</td>
<td>–</td>
</tr>
<tr>
<td>9</td>
<td>NaBH(OAc)₃ (2 equiv), HC(OEt)₂–CH₂Cl₂, 1:1, 20 °C, 23 h</td>
<td>19</td>
<td>–</td>
</tr>
<tr>
<td>10</td>
<td>1. Na₂SO₄ (10 equiv), AcOH, 20 °C, 40 min 2. NaBH(OAc)₃ (3 equiv), 20 °C, 24 h</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>NaBH(OAc)₃ (2 equiv), AcOH (1 equiv), toluene, 20 °C, 6 d</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>NaBH(OAc)₃ (2.8 equiv), AcOH (5 equiv), DCE, 20 °C, 30 h</td>
<td>5b</td>
<td>+</td>
</tr>
<tr>
<td>13</td>
<td>Hantzsch ester (1.5 equiv), thiourea (0.1 equiv), 4 Å MS, toluene, 50 °C, 20 h</td>
<td>7b</td>
<td>+</td>
</tr>
<tr>
<td>14</td>
<td>1.5 equiv BH₃·THF, CH₂Cl₂–AcOH, 2:1, 20 °C, 3 d</td>
<td>9b</td>
<td>++</td>
</tr>
</tbody>
</table>

*a Key: – no conversion, 0 moderate conversion, + good conversion, ++ full conversion.

*b Methyl 3-oxocyclohexane-1-carboxylate was used as the ketone.
Results and Discussion

Reductive amination is one of the most frequently used synthetic reactions for the production of secondary (and tertiary) amines.5–9 The advantages over other transformations are the ready accessibility of the starting materials and its selectivity avoiding overalkylation. A comprehensive review has been published in 2002,10 in which the reaction with sterically congested ketone substrates and the reductive amination with electron-deficient amine nucleophiles have been defined as the remaining challenges in this field. The problematic step is often the initial imine formation due to the unreactive nature of either the carbonyl or amine component. Specific examples which have been described as test cases are the reaction of 2,6-disubstituted anilines with aldehydes11 and aliphatic or alicyclic ketones,20 of camphor with benzylamine,20 and the reaction of a β-keto ester with 2-fluoroaniline12 (modest yield). Several methods which perform well specifically for the reductive amination of electron-deficient amines have been published.5a,c–g,13 We tested several of these methods for the reductive amination of methyl 2-amino-5-bromobenzoate and 3-oxocyclohexane-1-carbonitrile as model substrates (Table 1).5b,7b,8b,14–21 Most reactions failed or gave only low conversions of the starting materials due to the unreactive nature of the aromatic amine.

The methods which worked best for the synthesis of the phenazistatin A derivative in these initial screenings (Table 1) were investigated in detail. For further optimization the model reaction was simplified to methyl anthranilate and cyclohexanone (commercially available) and the reactions were repeated using the same procedures as described in Table 1 (entries 12–14). The results are listed in Table 2 (vide infra). The well-established NaBH(OAc)3 (STAB) method by Abdel-Magid,20 led to incomplete conversion of methyl anthranilate to the product 4 even after one week of reaction time (Table 2, entry 1). The transfer hydrogenation approach by Menche using the Hantzsch ester as hydride source and a thiourea organocatalyst,7b resulted in full conversion after six days at 50 °C (entry 2). The third method was the reductive amination using BH3·THF9b (or BH3·SMe2)9c in CH2Cl2/AcOH at room temperature, which has been described to enable the reaction of the very electron-deficient 2-nitroaniline with acetone (3 equiv) in excellent yields within 16–20 hours. However, our attempts to apply the non-optimized method for our model reaction led only to incomplete conversion. We observed that prolonged reaction time and increased carbonyl loading did not improve conversion, but increasing the amount of reductant ultimately led to full conversion. In our experience, a minimum of three equivalents of BH3·THF is needed to ensure full conversion for most substrates. When exploring the scope of this useful transformation with other substrates, optimized method A (1.5 equiv carbonyl substrate, 3 equiv BH3·THF) proved to be a reliable and versatile method for the reductive amination of a wide range of electron-deficient amines (entry 3). The detailed substrate scope will be described in the following sections.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Method</th>
<th>Temp</th>
<th>Time</th>
<th>Conversion (%)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NaBH(OAc),b</td>
<td>20 °C</td>
<td>7 d</td>
<td>77a</td>
<td>73</td>
</tr>
<tr>
<td>2</td>
<td>Hantzsch esterd</td>
<td>50 °C</td>
<td>6 d</td>
<td>100</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>Ae</td>
<td>0 °C</td>
<td>3 h</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>Bf</td>
<td>0 °C</td>
<td>15 min</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>5</td>
<td>Cg</td>
<td>0 °C</td>
<td>15 min</td>
<td>100</td>
<td>99</td>
</tr>
</tbody>
</table>

a Isolated yield. 
b According to Abdel-Magid et al.:20 aniline (1.0 equiv), ketone (2.0 equiv), AcOH (5 equiv), NaBH(OAc)3 (2.8 equiv), DCE, 20 °C. 
c n-Nonane was used as an internal standard. 
d According to Menche et al.:7b aniline (1.0 equiv), cyclohexanone (1.5 equiv), Hantzsch ester (1.5 equiv), thiourea (0.1 equiv), 5 Å MS, toluene, 50 °C. 
e Method A: aniline (1.00 mmol), cyclohexanone (1.50 mmol), BH3·THF (3.0 mmol, 3.0 equiv), CH2Cl2–AcOH, 2:1, 0–20 °C. 
f Method B: aniline (300 μmol, 1.0 equiv), cyclohexanone (330 μmol, 1.1 equiv), TMSCl (750 μmol, 2.5 equiv), BH3·THF (300 μmol, 1.0 equiv), DMF, 0 °C. 
g Method C: aniline (300 μmol, 1.0 equiv), cyclohexanone (330 μmol, 1.1 equiv), TMSCl (750 μmol, 2.5 equiv), NaBH4 (300 μmol, 1.0 equiv), DMF, 0 °C.

When applying method A for the synthesis of various Phenazistatin derivatives using substituted arylamines and cyclohexanones, we sometimes obtained lower yields and noticed the formation of two byproducts, namely N-acetylated and N-ethylated aniline substrate (Scheme 2). Such by-products have been previously reported for the NaBH(OAc)3 method by Abdel-Magid when AcOH was used as Lewis acid. In fact, protocols for the N-ethylation of amines using NaBH4 in neat carboxylic acid have been reported in the literature.22–24 It is suggested that the product originates from a stepwise process in which acetic acid is reduced to acetaldehyde (or an acetaldehyde equivalent), which reacts with the amine to form an iminium ion. Reduction of this imine results in the ethylamine product.22 Marchini could isolate the N-acetylated product by heating the NaBH4-carboxylic acid mixture before addition of the amine.24 During the synthesis of Phenazistatin derivative 1, we observed the formation of these byproducts (2 and 3), which accounted for considerable consumption of the substrate arylamine (Scheme 2).
We reasoned that by using a different acid additive we might suppress these side reactions and increase the yields. Full conversion was obtained with the acids (9 equiv each) TFA (12 h), MeSO₃H (3 d), malonic acid (13 h), and phenylphosphonic acid (13 h) and the activating agent TMSCl (12 h) for the reaction of 2-aminobenzonitrile and 4-tert-butylcyclohexanone in rates similar to AcOH (12 h). Among these reagents, TMSCl proved to be the most attractive substitute for AcOH due to its availability, low molecular weight, low price, and, most importantly, by its lack of the formation of the common byproducts mentioned above for AcOH. TMSCl has been used extensively in combination with boranes for the reduction of carbonyl substrates, along with borohydrides mainly for the in situ generation of borane.25 Blacklock had used TMSCl as an additive for the reductive alkylation of ureas, thioureas, and carbamates (with benzaldehydes, NaBH₄ in AcOH).26 By screening different solvents we observed that DMF increases the reaction rate significantly and lowers the extent of carbonyl reduction. Optimization of the reaction parameters resulted in optimized method B (1.1 equiv carbonyl substrate, 2.5 equiv TMSCl, 1.0 equiv BH₃·THF), which gave 97% yield in 15 minutes at 0 °C for the model reaction (Table 2, entry 4). It is noteworthy that the reaction proceeds to completion within minutes at 0 °C. An amount of 1.0 equiv of BH₃·THF sufficed for all tested reactions, but full conversion was detected for the reaction of 2-aminobenzonitrile with cyclohexanone even when only 0.5 equiv BH₃·THF was used. The reductive amination was carried out at high concentrations of the arylamine in DMF (1.5 M) but was found to perform equally well in higher dilutions (0.5 M). We kept the solvent volume at a minimum to facilitate the removal of DMF during workup.

One parameter which requires special attention is the reducing agent borane–tetrahydrofuran complex. BH₃·THF is commonly used as a 1.0 M solution in THF (stabilized with NaBH₄),27 which is stable when stored and used at 0 °C, but loses hydride activity when kept at room temperature, creating a stability and safety concern. While BH₃·THF can be conveniently handled in a research laboratory, it would be desirable to substitute BH₃·THF by a more inexpensive and inherently safer reducing agent for largescale applications.28,29 We conducted a screening of commonly employed hydride sources in combination with TMSCl as activating agent (Table 3).

### Table 3 Test Reaction with Different Hydride Sources

<table>
<thead>
<tr>
<th>Entry</th>
<th>Reducing agent</th>
<th>Conversion (%)</th>
<th>Yield (%)</th>
<th>Price [€/mol H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PMHS</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Et₃SiH</td>
<td>0</td>
<td>0</td>
<td>108</td>
</tr>
<tr>
<td>3</td>
<td>PhSiH₃</td>
<td>100</td>
<td>84</td>
<td>218</td>
</tr>
<tr>
<td>4</td>
<td>NaBH₄</td>
<td>100</td>
<td>88</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>NaBH(OAc)₃</td>
<td>92</td>
<td>66</td>
<td>207</td>
</tr>
<tr>
<td>6</td>
<td>BH₃·THF</td>
<td>100</td>
<td>90</td>
<td>64</td>
</tr>
<tr>
<td>7</td>
<td>pinacolborane</td>
<td>100</td>
<td>91</td>
<td>350</td>
</tr>
<tr>
<td>8</td>
<td>9-BBN⁺</td>
<td>88</td>
<td>81</td>
<td>496</td>
</tr>
<tr>
<td>9</td>
<td>catecholborane</td>
<td>77</td>
<td>73</td>
<td>727</td>
</tr>
</tbody>
</table>

*¹ 1,2-DME was used as an internal standard.
*² Isolated yield.
*³ Prices from Sigma-Aldrich catalog November 2015.
*⁴ 1.0 M solution in THF.
*⁵ 0.5 M solution in THF.

PMHS and Et₃SiH did not react under the reaction conditions of method B (Table 3, entries 1 and 2), while PhSiH₃ and the boron-based reductants resulted in good to high conversions and yields (entries 3–9). To our delight, NaBH₄ performed equally well compared to BH₃·THF in the reductive amination (entries 4 and 6), allowing us to define the cost-efficient method C (TMSCl, NaBH₄, DMF, 0 °C), as the price per hydride equivalent of NaBH₄ is significantly lower than for any other active reductant, with BH₃·THF the second least expensive one. In order to explore the substrate scope, we conducted a series of experiments using method C. The results are summarized in the following section. In Table 2 we have compared the performance of the best established procedures in the literature with our new methods A–C for the same test substrate. Methods A–C deliver product 4 in much shorter reaction times and lower reaction temperatures.

So far, all reported reactions have been performed in an anhydrous solvent under inert conditions. To test the sensitivity of method C towards moisture and air, we performed the reaction of methyl anthranilate with cyclohexanone in an open flask using synthesis-grade (99.8%) DMF. We were
pleased to find that the same yield as for the inert conditions was isolated after 15 minutes reaction time at 0 °C (see below, Table 4, entry 7C*).

On the basis of previous studies by Abdel-Magid, a Borch, b Roth, e and Schellenberg, b we propose a possible mechanism outlined in Scheme 3, suggesting a dual role of TMSCl. First, TMSCl activates the carbonyl substrate for nucleophilic attack by the amine. Second, it shifts the equilibrium to the imine by serving as a dehydrating agent, g which also provides the acid required for the formation of the iminium ion, which is the ultimate substrate for hydride attack (Scheme 3).

Scheme 3 Proposed mechanism of the reductive amination process

**Reductive Amination with Weakly Nucleophilic Amines**

The described methods are very efficient in reductive amination reactions with weakly basic and nonbasic amines. The results in Table 4 show that a wide range of arylamines can successfully react in the reductive amination with cyclohexanone. The reductive amination following the BH₃·THF/AcOH/CH₂Cl₂ method (Table 4, method A) with reaction times from 3–41 hours is generally slower than the BH₃·THF/TMSCI/DMF method (Table 4, method B) and the NaBH₄/TMSCI/DMF method (Table 4, method C), which typically require 10–230 minutes. It is noteworthy that method B and method C proceed at 0 °C within minutes while method A and other described methods for electron-deficient aromatic amines require room or even higher temperatures and reaction times of hours to days. We found that method B (BH₃·THF/DMF) and method C (NaBH₄/DMF) yielded comparable results for most of the aromatic amines tested; however, method B (BH₃·THF/DMF) was chosen for the study of reactive carbonyl groups in the next section (see below, Table 5), as the handling of the liquid BH₃·THF solution was more suitable for parallel operations on a small scale. While there is a significant difference between method A and method B/method C in matters of reactivity and reaction rate, we observed that the selectivity and tolerance for functional groups seem to be conserved in most cases.

### Table 4 Investigation of the Aniline Substrate Scope for Reductive Amination by Methods A, B, and C

<table>
<thead>
<tr>
<th>Entry</th>
<th>Amination Method</th>
<th>Time</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Method A/B/C</td>
<td>21 h</td>
<td>81</td>
</tr>
<tr>
<td>1B</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>85</td>
</tr>
<tr>
<td>1C</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>90</td>
</tr>
<tr>
<td>2B</td>
<td>Method B</td>
<td>140 min</td>
<td>0</td>
</tr>
<tr>
<td>2B*</td>
<td>Method B</td>
<td>230 min</td>
<td>66</td>
</tr>
<tr>
<td>2C</td>
<td>Method C</td>
<td>15 min</td>
<td>0</td>
</tr>
<tr>
<td>3A</td>
<td>Method A/B/C</td>
<td>19 h</td>
<td>77</td>
</tr>
<tr>
<td>3B</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>77</td>
</tr>
<tr>
<td>3C</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>70</td>
</tr>
<tr>
<td>4A</td>
<td>Method A/B/C</td>
<td>3 h</td>
<td>89</td>
</tr>
<tr>
<td>4B</td>
<td>Method A/B/C</td>
<td>10 min</td>
<td>72</td>
</tr>
<tr>
<td>5A</td>
<td>Method A/B/C</td>
<td>6 d</td>
<td>90</td>
</tr>
<tr>
<td>5B</td>
<td>Method A/B/C</td>
<td>18 min</td>
<td>90</td>
</tr>
<tr>
<td>5C</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>87</td>
</tr>
<tr>
<td>6B</td>
<td>Method A/B/C</td>
<td>10 min</td>
<td>91</td>
</tr>
<tr>
<td>6C</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>91</td>
</tr>
<tr>
<td>7A</td>
<td>Method A/B/C</td>
<td>3 h</td>
<td>80</td>
</tr>
<tr>
<td>7B</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>97</td>
</tr>
<tr>
<td>7C</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>99</td>
</tr>
<tr>
<td>7C*</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>99</td>
</tr>
<tr>
<td>8A</td>
<td>Method A/B/C</td>
<td>21 h</td>
<td>29</td>
</tr>
<tr>
<td>8B</td>
<td>Method A/B/C</td>
<td>15 min</td>
<td>79</td>
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The described methods give good yields for electron-rich primary amines and a wide range of electron-deficient primary aromatic amines. The reactions are convenient and simple and show a high degree of tolerance for a variety of functional groups including acetyl, alkoxycarbonyl, carboxy, cyano, diethylphosphonyl, halo, and nitro groups.

Substitution at the ortho position of aromatic amines did not seem to have any detrimental effect on the reaction rate, and high to excellent yields were obtained (Table 4). As mentioned above, the reductive amination of 2,6-disubstituted anilines has been described in the literature as a challenging substrate combination. The sterically hindered 2,6-dichloroaniline reacted very slowly by method A (entry 5A, 18% conversion after 6 d), but to our delight reacted smoothly by method B and method C, giving product 9 in 90% and 87% yield (entries 5B and 5C), respectively. The most sterically hindered aniline used, 2,6-disopropylamineline, failed to undergo reaction with cyclohexanone by both methods B and C (entries 2B and 2C). However, the reactivity of method B could be enhanced by the use of TMSOTf instead of TMSCl (entry 2B*). The reaction proceeded very slowly (230 min) but gave the product 6 in 66% yield.

The very electron-deficient 2-nitroaniline gave product 14 in 94% yield after 30 min at 0 °C by method B (Table 4, entry 11B). Abdel-Magid3b could only obtain 30% conversion to the desired product after 6 days at room temperature when using the optimized NaBH(OAc)3 conditions. Anthranilic acid reacted well by methods A and B to give product 10 in 91% yield (entries 6B and 6C). Interestingly, the heterocyclic arylamine 3-aminopyridine reacted to form the reductive amination product 15 in 84% yield by method B (entry 12B).

### Reductive Amination of Aldehydes and Ketones

The results in Table 5 show that the reductive amination of a variety of aromatic aldehydes as well as cyclic and acyclic ketones with the electron-deficient anilines H and I was successfully accomplished under the standard conditions (methods A and B) and furnished the products in moderate to excellent yields. The scope of the reaction includes different aromatic aldehydes (entries 1A, 1B, and 2B), cinnamic aldehyde (entry 3B), alicyclic ketones (entries 5A, 8A, 9A, and 4B–9B), 2-adamantanone (entries 9A and 9B), saturated acyclic ketones (entries 10A, 11A, 11B, 12B, and 13B*), methyl 3-oxobutanoate (entry 12B), acetophenone (entries 16A and 16B*) and 1,1-dioctethoxycyclohexane (entry 18B). For the same primary aromatic amine the rate of the reaction was dependent on the steric and electronic factors associated with the carbonyl substrates as well as with the reductive amination protocol used. The substrates reacted consistently more sluggishly when using the BH3·THF in CH2Cl2/AcOH system (method A) as compared to the BH3·THF/TMSCl/DMF system (method B).

Aldehydes and ketones are known to be reduced by BH3·THF30 and NaBH4,31 and thus carbonyl reduction could be expected to compete with the reductive amination process.3b However, the chosen reaction conditions were so selective that the reductive amination with aldehydes and ketones worked efficiently and resulted in clean reactions in most cases. Cases in which carbonyl reduction was detected involved the sterically hindered 2-tert-butylcyclohexan-1-one in both methods A and B (Table 5, entries 14A, 14B, and 14B*), 2,6-disopropylaniline in the modified method B (Table 4, entry 2B*), and acetophenone when using the modified method B (Table 5, entry 16B*).

Of all the carbonyl substrates used in this study, the alicyclic ketones were the most reactive and gave very good to excellent yields (Table 5, entries 5A–9A and 4B–9B). Aldehydes gave somewhat lower yields with comparable reac-

---

**Table 4 (continued)**

<table>
<thead>
<tr>
<th>Amine</th>
<th>Product</th>
<th>Entry</th>
<th>Method*–c</th>
<th>Time</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>A</td>
<td>12</td>
<td>9A</td>
<td>A</td>
<td>3 h</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9B</td>
<td>B</td>
<td>10 min</td>
<td>68</td>
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<td></td>
<td></td>
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<td>67</td>
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<td></td>
<td>13</td>
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<td>A</td>
<td>15 h</td>
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<td>B</td>
<td>18 min</td>
<td>94</td>
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<td>C</td>
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<td>11B</td>
<td>B</td>
<td>30 min</td>
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<td></td>
<td></td>
<td>11C</td>
<td>C</td>
<td>30 min</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>12B</td>
<td>B</td>
<td>11 min</td>
<td>84</td>
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</tbody>
</table>

* Method A: amine (1.00 mmol), cyclohexanone (1.50 mmol), BH3·THF (3.0 mmol, 3.0 equiv), CH2Cl2/AcOH, 2:1, 0–20 °C.
* Method B: amine (300 μmol, 1.0 equiv), cyclohexanone (330 μmol, 1.1 equiv), TMSCl (750 μmol, 2.5 equiv), BH3·THF (300 μmol, 1.0 equiv), DMF, 0 °C.
* Method C: amine (300 μmol, 1.0 equiv), cyclohexanone (330 μmol, 1.1 equiv), TMSCl (750 μmol, 2.5 equiv), NaBH4 (300 μmol, 1.0 equiv), DMF, 0 °C.
* Isolated yield.
* TMSOTf was used instead of TMSCl.
* Cyclohexanone (1.5 equiv) was used.
* Carbonyl reduction was observed.
* Conversion of the starting material (n-nonane used as internal standard).
* Performed in an open flask using synthesis-grade DMF (99.8%).
tion times (entries 1A and 1B–3B), but, in contrast to established silane-based methods, we did not observe any overalkylated products. trans-Cinnamaldehyde reacted smoothly with methyl anthranilate providing 19 in 81% yield with no trace of C=C reduction product (entry 3B), which is a common side reaction with borane reagents. Saturated acyclic ketones reacted more sluggishly and gave lower yields (entries 10A, 11A, 11B, and 13B*). The β-keto ester methyl 3-oxobutanoate (entry 12B) reacted slowly and gave product 29 in 67% yield. The acid-labile ketone 1-Boc-3-piperidone reacted well with methyl anthranilate by method A, producing 23 (66%) (entry 8A), whereas method C yielded a complex mixture. Method A might be the better method for the coupling of more acid-sensitive carbonyl and arylamine substrates.

Table 5 (continued) Investigation of the Carbonyl Substrate Scope for Reductive Amination by Methods A and B

<table>
<thead>
<tr>
<th>Carbonyl reagent</th>
<th>Entry</th>
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<tr>
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<td>1B</td>
<td>H</td>
<td>B</td>
<td>20 min</td>
<td>17</td>
<td>85</td>
</tr>
<tr>
<td>N</td>
<td>2B</td>
<td>H</td>
<td>B</td>
<td>10 min</td>
<td>18</td>
<td>84</td>
</tr>
<tr>
<td>N</td>
<td>3B</td>
<td>H</td>
<td>B</td>
<td>10 min</td>
<td>19</td>
<td>81</td>
</tr>
<tr>
<td>O</td>
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<td>H</td>
<td>B</td>
<td>15 min</td>
<td>20</td>
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<td>5A</td>
<td>I</td>
<td>A</td>
<td>15 h</td>
<td>13</td>
<td>94</td>
</tr>
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<td>41 h</td>
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<td>0</td>
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<tr>
<td>O</td>
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<td>H</td>
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<td>20 h</td>
<td>–</td>
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</tr>
<tr>
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<td>18B</td>
<td>H</td>
<td>B</td>
<td>19 min</td>
<td>4</td>
<td>71h</td>
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</table>

a Method A: amine (1.0 mmol), cyclohexanone (1.5 mmol), BH3·THF (3.0 mmol, 3.0 equiv), CH2Cl2–AcOH, 2:1, 0–20 °C.
b Method B: amine (300 μmol, 1.0 equiv), cyclohexanone (330 μmol, 1.1 equiv), TMSCl (750 μmol, 2.5 equiv), BH3·THF (300 μmol, 1.0 equiv), DMF, 0 °C.
c Isolated yield.
d TMSOTf was used instead of TMSCl.
e Cyclohexanone (1.5 equiv) was used.
f Carbonyl reduction was observed.
g Product mass was identified by GC-MS (<5%).
h Methyl 2-(cyclohexylamino)benzoate was obtained as the product.
Reductive Amination of Aromatic and Sterically Hindered Ketones

The least reactive ketones were aromatic and sterically hindered alicyclic and aliphatic ketones. It is noteworthy that acetophenone reacted smoothly by method A to give the desired product 31 in good yield, whereas the unmodified method B failed (Table 5, entries 16A and 16B). For other unreactive carbonyl substrates, the aryamine substrate was quantitatively acetylated to the byproduct N-[(2-cyano-phenyl)acetamide, as judged by GC-MS (entries 14A, 15A, and 17A). The formation of small amounts of these byproducts was also described for some slow reactions when using the established NaBH(OAc)₃-protocol. Benzophenone, 2-((tert-butyl)cyclohexan-1-one, and (+)-camphor failed to react with 2-aminobenzonitrile by method A (entries 14A, 15A, and 17A). These substrates as well as acetophenone and benzophenone could also not be converted in the reaction with methyl anthranilate by method B (entries 13B, 14B, 15B, 16B, and 17B).

However, the reactivity could be enhanced by using the more reactive TMSOTf instead of TMSCl as demonstrated for the reaction with pinacolone and acetophenone giving products 30 and 32 in good yields (entries 13B* and 16B*) after reaction times of 20 and 23 hours, respectively. However, even with the TMSOTF-modified method B, the other challenging ketones hardly reacted with methyl anthranilate, and only traces (<5%) of the desired products were detected by GC-MS (entries 14B*, 15B*, and 17B*) after 18–23 hours. Interestingly, method B can also be used for the reductive amination with ketals, as exemplified for 1,1-diethoxycyclohexane as a substrate (entry 18B).

To demonstrate the scalability of method B, the gram-scale synthesis of the Phenazistatin derivatives 33 and 34 (Figure 3) was performed, which delivered 33 and 34 in 96% and 97% yield, respectively, in the short reaction times observed for the model reactions.

![Figure 3](image)

Summary and Conclusions

In conclusion, we have established three new methods which have proven useful for the reductive amination of electron-deficient anilines with ketones. Method A (BH₃THF/AcOH/CH₂Cl₂) is distinguished by inexpensive reagents and simple workup, but requires longer reaction times and gives rise to acetylated byproducts for substrate combinations with slow imine formation. For these substrates, the more reactive activating agent TMSCl is recommended, and both method B (BH₃THF/TMSCl/DMF) as well as method C (NaBH₄/TMSCl/DMF) offer powerful reagent combinations, which result in full conversions for most substrates within 10–25 minutes. In case these methods fail, the use of TMSOTf offers an additional possibility to make sterically more congested substrates accessible. Together, these methods have expanded the scope of the reductive amination reaction, which will become an even more powerful tool for the organic synthesis of substituted amines.
Method B: Reductive Amination of Arylamines and Aldehydes/Ketones with BH₃·THF and TMSI in DMF; General Procedure B

A dry 20 mL Schlenk tube with magnetic stirring bar was charged consecutively with arylamine (300 μmol, 1.0 equiv), carbonyl substrate (330 μmol, 1.1 equiv), anhyd DMF (200 μL), and TMSI (96.8 μL, 750 μmol, 2.5 equiv) in a N₂ counter-stream. The reaction mixture was cooled to 0 °C, the glass stopper was replaced by a rubber septum, and a 1.0 M solution of BH₃·THF in THF (300 μL, 300 μmol, 1.0 equiv) was added slowly with a syringe over a period of 10–20 min. The flask was sealed with a glass stopper and the reaction mixture was kept stirring at 0 °C until full conversion was detected by TLC. The vigorously stirred reaction mixture was treated with H₂O (3 mL) and the mixture was stirred for 20 min. EtOAc (5 mL) was added followed by sat. Na₂CO₃ solution (2.5 mL) (CO₂ evolution!). The two-phase mixture was kept stirring until the gas evolution had ceased (typically 20–60 min). In case the aqueous phase was turbid, small amounts of H₂O were added to provide a clear aqueous phase. The phases were separated and the aqueous layer was extracted with EtOAc (5 × 8 mL). The combined organic layers were dried over Na₂SO₄, the solvents were removed under vacuum, and the crude product (adsorbed onto Celite) was purified by chromatography (silica gel, cyclohexane–EtOAc, gradient).

Method C: Reductive Amination of Arylamines and Aldehydes/Ketones with NaBH₄ and TMSI in DMF; General Procedure C

A dry 20 mL Schlenk tube with magnetic stirring bar was charged consecutively with arylamine (1.0 mmol, 1.0 equiv), carbonyl substrate (1.1 mmol, 1.1 equiv), anhyd DMF (670 μL), and TMSI (323 μL, 2.5 mmol, 2.5 equiv) in a N₂ counter-stream. The reaction mixture was cooled to 0 °C and NaBH₄ (39.0 mg, 1.0 μmol, 1.0 equiv) was added in one portion. The flask was sealed with a glass stopper and the reaction mixture was kept stirring at 0 °C until full conversion was detected by TLC. The vigorously stirred reaction mixture was treated with sat. NaHCO₃ solution (5 mL) (CO₂ evolution!) followed by EtOAc (5 mL). The two-phase mixture was kept stirring until the gas evolution had ceased (typically 20–60 min). In case the aqueous phase was turbid, small amounts of H₂O were added to provide a clear aqueous phase. The phases were separated and the aqueous layer was extracted with EtOAc (5 × 10 mL). The combined organic layers were dried over Na₂SO₄, the solvents were removed by using a rotary evaporator. The solvents were removed under vacuum and the crude product (adsorbed onto Celite) was purified by chromatography (silica gel, cyclohexane–EtOAc, gradient).

Method B: Reductive Amination of Arylamines and Aldehydes/Ketones with BH₃·THF and TMSI in DMF; General Procedure B

A dry 20 mL Schlenk tube with magnetic stirring bar was charged consecutively with arylamine (300 μmol, 1.0 equiv), carbonyl substrate (330 μmol, 1.1 equiv), anhyd DMF (200 μL), and TMSI (96.8 μL, 750 μmol, 2.5 equiv) in a N₂ counter-stream. The reaction mixture was cooled to 0 °C, the glass stopper was replaced by a rubber septum, and a 1.0 M solution of BH₃·THF in THF (300 μL, 300 μmol, 1.0 equiv) was added slowly with a syringe over a period of 10–20 min. The flask was sealed with a glass stopper and the reaction mixture was kept stirring at 0 °C until full conversion was detected by TLC. The vigorously stirred reaction mixture was treated with H₂O (3 mL) and the mixture was stirred for 20 min. EtOAc (5 mL) was added followed by sat. Na₂CO₃ solution (2.5 mL) (CO₂ evolution!). The two-phase mixture was kept stirring until the gas evolution had ceased (typically 20–60 min). In case the aqueous phase was turbid, small amounts of H₂O were added to provide a clear aqueous phase. The phases were separated and the aqueous layer was extracted with EtOAc (5 × 8 mL). The combined organic layers were dried over Na₂SO₄, the solvents were removed under vacuum, and the crude product (adsorbed onto Celite) was purified by chromatography (silica gel, cyclohexane–EtOAc, gradient).

Method C: Reductive Amination of Arylamines and Aldehydes/Ketones with NaBH₄ and TMSI in DMF; General Procedure C

A dry 20 mL Schlenk tube with magnetic stirring bar was charged consecutively with arylamine (1.0 mmol, 1.0 equiv), carbonyl substrate (1.1 mmol, 1.1 equiv), anhyd DMF (670 μL), and TMSI (323 μL, 2.5 mmol, 2.5 equiv) in a N₂ counter-stream. The reaction mixture was cooled to 0 °C and NaBH₄ (39.0 mg, 1.0 μmol, 1.0 equiv) was added in one portion. The flask was sealed with a glass stopper and the reaction mixture was kept stirring at 0 °C until full conversion was detected by TLC. The vigorously stirred reaction mixture was treated with sat. NaHCO₃ solution (5 mL) (CO₂ evolution!) followed by EtOAc (5 mL). The two-phase mixture was kept stirring until the gas evolution had ceased (typically 20–60 min). In case the aqueous phase was turbid, small amounts of H₂O were added to provide a clear aqueous phase. The phases were separated and the aqueous layer was extracted with EtOAc (5 × 10 mL). The combined organic layers were dried over Na₂SO₄, the drying agent was removed by filtration, and the solvents were removed under vacuum. The crude product (adsorbed onto Celite) was purified by chromatography (silica gel, cyclohexane–EtOAc, gradient).

Methyl 2-(Cyclohexylamino)benzoate (4)

Prepared according to general procedure A from methyl anthranilate (39.2 μL, 300 μmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 200:1, 150:1, size: 7.5 × 2.2 cm); yield: 69.1 mg (296 μmol, 93%); light-yellow, viscous liquid.


N-Cyclohexyl-2-methoxylaniline (5)

Prepared according to general procedure A from 2-methoxylaniline (114 μL, 1.00 mmol); 21 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 40:1, size: 11 × 2.8 cm); yield: 166 mg (810 μmol, 81%); amorphous, colorless solid.

Prepared according to general procedure B from 2-methoxylaniline (34.2 μL, 300 μmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 100:1, size: 14 × 0.8 cm); yield: 52.6 mg (256 μmol, 85%); amorphous, colorless solid.

Prepared according to general procedure C from 2-methoxylaniline (114 μL, 1.00 mmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 100:1, 50:1, size: 20 × 1.4 cm); yield: 184 mg (902 μmol, 90%); amorphous, colorless solid; mp 32 °C; [M]⁺ = 0.31 (cyclohexane–EtOAc, 3:1) (254 nm, 366 nm, CAM: purple).

IR (ATR): 3422, 2919, 2849, 1600, 1507, 1449, 1252, 1234, 1219, 1125, 1026, 738 cm⁻¹.


N-Cyclohexyl-2,6-diisopropylaniline (6)

Prepared according to general procedure B from 2,6-diisopropylaniline (62.9 μL, 300 μmol) using TMSOTf (139 μL, 750 μmol) instead of TMSI; 230 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 100:1, size: 8 × 0.8 cm); yield: 51.6 mg (199 μmol, 66%); colorless, viscous liquid; [M]⁺ = 0.76 (cyclohexane–EtOAc, 9:1) (254 nm, K₅MO₃: yellow).

The spectra (see SI) were in accordance with the previously reported data.²¹

N-Cyclohexylaniline (7)

Prepared according to general procedure A from aniline (92.0 μL, 1.00 mmol); 19 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 45:1, size: 11 × 2.8 cm); yield: 134 mg (765 μmol, 77%); light-yellow, viscous liquid.
Prepared according to general procedure B from aniline (27.7 μL, 300 μmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 150:1, size: 14 × 0.8 cm); yield: 40.4 mg (230 μmol, 77%); light-yellow, viscous liquid.

Prepared according to general procedure C from aniline (92.0 μL, 1.00 mmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 45:1, size: 15.5 × 3.5 cm); yield: 123 mg (702 μmol, 70%); light-yellow, viscous liquid.

\( R_f = 0.79 \) (cyclohexane–EtOAc, 3:1) (254 nm, CAM: carnate).

The spectra (see SI) were in accordance with the previously reported data.33

Diethyl [2-(Cyclohexylamino)phenyl]phosphonate (8)
Prepared according to general procedure A from diethyl (2-amino-phenyl)phosphonate34 (229 mg, 1.00 mmol); 3 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 400:1, size: 14 × 0.8 cm); yield: 66.0 mg (270 μmol, 72%); light-yellow, viscous liquid.

Prepared according to general procedure B from diethyl (2-amino-phenyl)phosphonate (68.8 mg, 300 μmol); 10 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 5:1, size: 15 × 0.8 cm); yield: 67.6 mg (217 μmol, 72%); light-yellow, viscous liquid.

\( R_f = 0.24 \) (cyclohexane–EtOAc, 5:1) (254 nm, 366 nm, CAM: blue).

IR (ATR): 3324, 2924, 2914, 2852, 1648, 1584, 1569, 1451, 1431, 1359, 1299, 1257, 1170, 1147, 1106, 1069, 953, 823, 611, 568, 498, 468 cm⁻¹.

\( \delta \) (Cq), 142.1 (Cq), 111.6, 51.4, 33.2, 26.0, 25.8, 24.9, 23.0 mg, 72%); light-yellow solid.

Mp 115–117 °C, \( R_f = 0.43 \) (cyclohexane–EtOAc, 3:1) (254 nm).

HR-MS (GC-EI): \( m/z \) [M⁺] calcld for C₁₂H₁₅Cl₂N: 243.0582; found: 243.0582.

\( \text{2-(Cyclohexylamino)benzoic Acid (10)} \)
Prepared according to general procedure B from anthranilic acid (42.0 mg, 300 μmol); 10 min reaction time; purified by column chromatography (cyclohexane–EtOAc–AcOH, 100:10:1, size: 15 × 0.8 cm); yield: 59.9 mg (273 μmol, 91%); light-yellow solid.

Prepared according to general procedure C from anthranilic acid (140 mg, 1.00 mmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc–AcOH, 100:10:1; size: 15 × 3.5 cm); yield: 200 mg (912 μmol, 91%); light-yellow solid.

Mp 116 °C, \( R_f = 0.18 \) (cyclohexane–EtOAc–AcOH, 100:10:1) (254 nm, 366 nm, CAM: orange-green).

The spectra (see SI) were in accordance with the previously reported data.35

1-[(4-(Cyclohexylamino)phenyl)ethan-1-one (11)
Prepared according to general procedure A from 4-aminocetophenone (138 mg, 1.00 mmol); 21 h reaction time, purified by column chromatography (cyclohexane–EtOAc, 40:1, size: 13 × 2.8 cm); yield: 62.5 mg (288 μmol, 29%); light-orange, sticky solid.

Prepared according to general procedure B from 4-aminocetophenone (41.4 mg, 300 μmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 9:1, size: 15 × 0.8 cm); yield: 51.5 mg (237 μmol, 79%); light-yellow solid.

Mp 115–117 °C, \( R_f = 0.37 \) (cyclohexane–EtOAc, 9:1) (254 nm).

HR-MS (GC-EI): \( m/z \) [M⁺] calcld for C₁₄H₁₉NO: 217.1467; found: 217.1470.

N-Cyclohexyl-2-fluoro-5-(trifluoromethyl)aniline (12)
Prepared according to general procedure A from 2-fluoro-5-(trifluoromethyl)aniline (134 μL, 1.00 mmol); 3 h reaction time; purified by column chromatography (cyclohexane, size: 9.5 × 3.6 cm); yield: 187 mg (717 μmol, 72%); colorless, viscous liquid.

Prepared according to general procedure B from 2-fluoro-5-(trifluoromethyl)aniline (40.2 μL, 300 μmol); 10 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 300:1; size: 15 × 0.8 cm); yield: 53.2 mg (204 μmol, 68%); colorless, viscous liquid.

Prepared according to general procedure C from 2-fluoro-5-(trifluoromethyl)aniline (134 μL, 1.00 mmol); 15 min reaction time; purified by column chromatography (cyclohexane, size: 15.5 × 3.0 cm); yield: 174 mg (666 μmol, 67%); light-yellow, viscous liquid.

\( R_f = 0.85 \) (cyclohexane–EtOAc, 3:1) (254 nm, KMnO₄ yellow).

IR (ATR): 3435, 2932, 2857, 1624, 1534, 1444, 1351, 1322, 1302, 1283, 1259, 1240, 1195, 1161, 1091, 1066, 934, 853, 805, 658, 625, 610 cm⁻¹.
2-[(Benzyloxylamino)benzonitrile] (16)
Prepared according to general procedure A from 2-aminobenzenitrile (121 mg, 1.00 mmol) and benzaldehyde (155 µL, 1.5 mmol); 15 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 30:1; size: 11 × 2.6 cm); yield: 167 mg (803 µmol, 80%); colorless solid; mp 110–112 °C; \( R_f = 0.15 \) (cyclohexane–EtOAc, 30:1) (254 nm, 366 nm, CAM: violet-grey).

The spectra (see SI) were in accordance with the previously reported data.\(^{39}\)

Methyl 2-(Benzyloxylamino)benzoate (17)
Prepared according to general procedure B from methyl anthranilate (39.2 µL, 300 µmol) and benzaldehyde (33.9 µL, 330 µmol); 20 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 100:1, 70:1; size: 12 × 2.4 cm); yield: 61.6 mg (255 µmol, 85%); light-yellow, very viscous liquid; \( R_f = 0.72 \) (cyclohexane–EtOAc, 4:1) (254 nm, 366 nm).

IR (ATR): 3386, 3362, 3023, 3003, 2947, 2844, 1675, 1605, 1575, 1513, 1494, 1453, 1434, 1323, 1287, 1225, 1187, 1166, 1147, 1102, 1077, 753, 728, 703, 693, 595, 566, 527, 458 cm⁻¹.

1H NMR (300 MHz, CDCl₃); \( \delta = 8.09 \) (br s, 1 H, NH), 7.84 (dd, \( J_{HH} = 8.0 \) Hz, \( J_{HH} = 1.3 \) Hz, 1 H, ArH), 7.36–7.12 (m, 6 H, ArH), 6.63–6.45 (m, 2 H, ArH), 4.37 (s, 2 H, CH₂), 3.78 (s, 3 H, CH₃).


Methyl 2-[(Pyridin-3-ylmethyl)amino]benzoate (18)
Prepared according to general procedure B from methyl anthranilate (39.2 µL, 300 µmol) and 3-pyridinecarboxaldehyde (31.6 µL, 330 µmol); 10 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 3:1, 2.1:1; size: 15 × 0.8 cm); yield: 61.1 mg (252 µmol, 84%); light-yellow, viscous liquid; \( R_f = 0.16 \) (cyclohexane–EtOAc, 2:1) (254 nm, 366 nm).

IR (ATR): 3380, 2945, 2840, 1680, 1607, 1586, 1516, 1494, 1453, 1434, 1323, 1287, 1225, 1187, 1166, 1147, 1102, 1077, 753, 728, 703, 693, 595, 566, 527, 458 cm⁻¹.

1H NMR (300 MHz, CDCl₃); \( \delta = 8.70–8.62 \) (m, 1 H, ArH), 8.55 (d, \( J_{HH} = 3.9 \) Hz, 1 H, ArH), 8.23 (br s, 1 H, NH), 7.96 (dd, \( J_{HH} = 8.0 \) Hz, \( J_{HH} = 1.2 \) Hz, 1 H, ArH), 7.70 (d, \( J_{HH} = 7.8 \) Hz, 1 H, ArH), 7.39–7.23 (m, 2 H, ArH), 6.71–6.58 (m, 2 H, ArH), 4.50 (d, \( J_{HH} = 5.5 \) Hz, 2 H, CH₂), 3.89 (s, 3 H, CH₃).

HR-MS (GC-EI): \( m/z \) [M⁺] calcd for C₁₃H₁₂N₂O₂: 241.1103; found: 241.1108.

N-Cyclohexyl-2-nitroaniline (14)
Prepared according to general procedure A from 2-nitroaniline (42.3 mg, 300 µmol); 30 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 80:1; size: 7.5 × 2.2 cm); yield: 51.5 mg (234 µmol, 78%); bright-orange solid.

Mp 101–103 °C; \( R_f = 0.70 \) (cyclohexane–EtOAc, 2:1) (254 nm, VIS: orange).

The spectra (see SI) were in accordance with the previously reported data.\(^{37}\)

N-Cyclohexylpyridin-3-amine (15)
Prepared according to general procedure B from 3-aminopyridine (28.5 mg, 300 µmol); 11 min reaction time; purified by column chromatography (CH₂Cl₂–MeOH, 80:1; size: 13 × 1 cm); yield: 44.2 mg (251 µmol, 84%); light-beige solid; mp 86–89 °C; \( R_f = 0.20 \) (CH₂Cl₂–MeOH, 80:1) (254 nm, 366 nm, KMMO₂; yellow).

The spectra (see SI) were in accordance with the previously reported data.\(^{38}\)
Methyl 2-(Cyclopentylamino)benzoate (20)
Prepared according to general procedure B from methyl anthranilate (39.2 μL, 300 μmol) and cyclopentanone (29.5 μL, 330 μmol); 15 min reaction time; purified by column chromatography (cyclohexane–EtOAc, 200:1, size: 8 × 0.8 cm); yield: 67.5 mg (273 μmol); 44 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 20:1; size: 20 × 0.8 cm); yield: 220 mg (657 μmol); 44 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 120:1, size: 20 × 1.2 cm); yield: 96.0 mg (300 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 150:1, size: 20 × 1.2 cm); yield: 87.8 mg (283 μmol); 44 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 20:1, size: 20 × 1.2 cm); yield: 25.6 mg (80 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 9:1, size: 20 × 0.8 cm); yield: 24.2 mg (78 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 3:1, size: 20 × 1.2 cm); yield: 15.2 mg (50 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 150:1, size: 20 × 1.2 cm); yield: 16.2 mg (50 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:1, size: 20 × 1.2 cm); yield: 12.0 mg (38 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:2, size: 20 × 1.2 cm); yield: 10.0 mg (33 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 9:1, size: 20 × 1.2 cm); yield: 9.0 mg (30 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 3:1, size: 20 × 1.2 cm); yield: 7.0 mg (24 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 150:1, size: 20 × 1.2 cm); yield: 6.0 mg (20 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:1, size: 20 × 1.2 cm); yield: 5.0 mg (17 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:2, size: 20 × 1.2 cm); yield: 4.0 mg (14 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 9:1, size: 20 × 1.2 cm); yield: 3.0 mg (10 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 3:1, size: 20 × 1.2 cm); yield: 2.0 mg (7 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 150:1, size: 20 × 1.2 cm); yield: 1.0 mg (3 μmol); 41 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:1, size: 20 × 1.2 cm); yield: 0.8 mg (3 μmol).
Prepared according to general procedure A from 2-aminobenzonitrile (121 mg, 1.00 mmol) and 2-pentanone (164 μL, 1.5 mmol); 39 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 50:1; size: 11 × 2.6 cm); yield: 150 mg (795 μmol, 80%); light-yellow, sticky solid; Rf = 0.31 (cyclohexane–EtOAc, 30:1) (254 nm, 366 nm, CAM: yellow).

IR (ATR): 3407, 3363, 2960, 2931, 2872, 2210, 1604, 1575, 1512, 1461, 1380, 1342, 1289, 1167, 1042, 744, 568, 495 cm⁻¹.

¹H NMR (300 MHz, CDCl₃): δ = 7.43–7.28 (m, 2 H, ArH), 6.72–6.54 (2 H, ArH), 4.30 (br s, 1 H, NH), 3.70–3.50 (m, 1 H, CH₂), 1.48–1.28 (m, 1 H, CH₂), 1.19 (d, JHH = 6.9 Hz, 3 H, CH₃), 1.02–0.80 (m, 6 H, 2 × CH₂).

¹C NMR (75.53 MHz, CDCl₃): δ = 149.9 (Cq), 134.3, 133.3, 118.2 (Cq), 116.0, 110.9, 95.7 (Cq), 46.6, 46.5, 25.1, 22.8, 22.7, 21.0.


Methyl 2-[4-Methoxy-4-oxobutan-2-yl]amino]benzoate (29)

Prepared according to general procedure B from methyl anthranilate (39.2 μL, 0.30 mmol) and methyl acetate (36.0 μL, 330 μmol); 6 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 17.1:1; size: 8 × 0.8 cm); yield: 50.8 mg (202 μmol, 67%); colorless, viscous liquid; Rf = 0.55 (cyclohexane–EtOAc, 3:1) (254 nm, 366 nm, CAM: orange-green).

IR (ATR): 3431, 2952, 1735, 1682, 1605, 1581, 1516, 1447, 1333, 1299, 1239, 1190, 1162, 1130, 1077, 1047, 1005, 748, 703, 527 cm⁻¹.

¹H NMR (300 MHz, CDCl₃): δ = 8.00–7.65 (m, 2 H, NH, ArH), 7.41–7.30 (m, 1 H, ArH), 6.75 (d, JHH = 8.5 Hz, 1 H, ArH), 6.59 (t, JHH = 7.3 Hz, 1 H, ArH), 4.16–3.99 (m, 1 H, CH₂), 3.85 (s, 3 H, CH₃), 3.69 (s, 3 H, CH₂), 2.73 (dd, JHH = 15.1 Hz, JHCH₂ = 5.0 Hz, 1 H, CH₂), 2.43 (dd, JHH = 15.1 Hz, JHCH₂ = 7.8 Hz, 1 H, CH₂), 1.33 (d, JHH = 6.4 Hz, 3 H, CH₃).

¹C NMR (75.53 MHz, CDCl₃): δ = 172.1 (Cq, C=12), 169.1 (Cq, C=9), 149.8 (Cq, C=8), 134.8 (C=14), 132.0 (C=12), 115.0 (C=11), 111.8 (C=10), 110.4 (C=9), 51.8 (CH₂), 51.6 (CH₃), 45.1 (C=10), 41.2 (C=9), 20.8 (C=9).

HR-MS: m/z [M⁺] calcd for C₁₃H₁₄NO₂: 235.1158; found: 235.1172.

Methyl 2-[3,3-Dimethylbutan-2-yl]amino]benzoate (30)

Prepared according to general procedure B from methyl anthranilate (39.2 μL, 0.30 mmol), pinacolone (57.4 μL, 450 μmol) and TMSOTf (139 μL, 750 μmol, instead of TMSCI); left stirring in the thawing ice bath; 20 h reaction time; purified by column chromatography (cyclohexane–EtOAc, 1:0, 120:1; size: 14 × 2.5 cm); yield: 35.2 mg (150 μmol, 50%); yellow, viscous liquid; Rf = 0.23 (cyclohexane–EtOAc, 120:1) (254 nm, 366 nm, CAM: orange-yellow).

IR (ATR): 3435, 2955, 2871, 1680, 1606, 1580, 1518, 1457, 1435, 1370, 1350, 1231, 1254, 1232, 1189, 1161, 1119, 1080, 1046, 745, 702, 520 cm⁻¹.

¹H NMR (300 MHz, CDCl₃): δ = 8.17–7.81 (m, 2 H, NH, ArH), 7.37–7.27 (m, 1 H, ArH), 6.73 (d, JHH = 8.6 Hz, 1 H, ArH), 6.51 (t, JHH = 7.4 Hz, 1 H, ArH), 3.85 (s, 3 H, CH₃), 3.45–3.30 (m, 1 H, CH₂), 1.14 (d, JHH = 6.5 Hz, 3 H, CH₃), 1.02 (s, 9 H, 3 × CH₃).

¹C NMR (75.53 MHz, CDCl₃): δ = 169.5 (Cq), 151.3 (Cq), 134.7, 132.0, 113.8, 111.6, 109.5 (Cq), 56.6, 51.6, 35.0 (Cq), 26.7, 15.7.

HR-MS: m/z [M⁺] calcd for C₁₄H₁₉NO₂: 235.1572; found: 235.1602.
IR (ATR): 3361, 3024, 2973, 2930, 2866, 2213, 1603, 1577, 1517, 1491, 1470, 1448, 1342, 1330, 1316, 1291, 1261, 1167, 1147, 1095, 1023, 947, 759, 741, 700, 608, 565, 541, 484, 445 cm⁻¹.

1H NMR (300 MHz, CDCl₃): δ = 7.41–7.14 (m, 4 H, ArH), 7.73 (d, 3 JHH = 8.5 Hz, 1 H, ArH), 4.89 (br s, 1 H, NH), 4.62–4.47 (m, 1 H, CH), 1.57 (d, 3 JHH = 6.7 Hz, 1 H, CH₃).

13C NMR (75.53 MHz, CDCl₃): δ = 149.4 (Cq), 143.8 (Cq), 134.2, 132.7, 129.0, 127.4, 125.7, 118.1 (Cq), 116.8, 112.1, 96.0 (Cq), 53.4, 52.2 cm⁻¹.

HR-MS (DI-EI): m/z [M]+ calcld for C₁₅H₁₄N₂: 222.1157; found: 222.1167.

Methyl 2-[(1-Phenylethyl)amino]benzoate (34)

A dry 100 mL Schlenk flask with magnetic stirring bar was charged with methyl 2-amino-5-iodobenzoate hydrochloride (6.69 g, 21.3 mmol, 1.0 equiv) and the solid was dried under an oil-pump vacuum for 10 min. To the Schlenk flask were added anhyd DMF (5 mL), methyl 2-amino-5-bromobenzoate (2.37 g, 10.7 mmol, 1.0 equiv) and TMSCl (8.30 mL, 64.0 mmol, 3.0 equiv). The glass stopper was replaced by a rubber septum, the flesh-colored, colorless, viscous liquid; Rf = 0.47 (cyclohexane–EtOAc, 254 nm, 366 nm, CAM: orange).

IR (ATR): 3364, 2936, 2860, 1730, 1683, 1575, 1502, 1435, 1314, 1215, 1188, 1113, 1079, 1042, 967, 883, 808, 788, 706 644, 564, 521 cm⁻¹.

1H NMR (300 MHz, CDCl₃): δ = 7.99 (d, 3 JHH = 2.3 Hz, 1 H, ArH), 7.71 (d, 3 JHH = 7.2 Hz, 1 H, ArH), 7.37 (d, 3 JHH = 9.0 Hz, 3 JHH = 2.2 Hz, 1 H, ArH), 6.58 (d, 3 JHH = 9.1 Hz, 1 H, ArH), 3.84 (s, 3 H, CH₃), 3.66 (s, 3 H, CH₃), 3.44–3.25 (m, 1 H, CH₂), 2.51–2.30 (m, 2 H, CH₂), 2.19–1.84 (m, 3 H, CH₂), 1.52–1.12 (m, 4 H, CH₂).

13C NMR (75.53 MHz, CDCl₃): δ = 175.3 (Cq), 168.1 (Cq), 149.1 (Cq), 137.2 (CH arom), 134.2 (CH arom), 113.6 (CH arom), 111.4 (Cq), 105.6 (Cq), 51.84, 51.81, 50.7, 42.5, 35.3, 32.6, 28.5, 24.4.

Methyl 5-iodo-2-[(3-methoxycarbonyl)cyclohexyl]amino]benzoate (34)

A dry 100 mL Schlenk flask with magnetic stirring bar was charged with methyl 2-amino-5-iodobenzoate hydrochloride (6.69 g, 21.3 mmol, 1.0 equiv) and the solid was dried under an oil-pump vacuum for 10 min. To the Schlenk flask were added anhyd DMF (40 mL) followed by methyl 3-oxocyclohexane-1-carboxylate (3.5 g, 22.4 mmol, 1.05 equiv) and TMSCl (8.30 mL, 64.0 mmol, 3.0 equiv). The glass stopper was replaced by a rubber septum, the flesh-colored, two-phase mixture was cooled with an ice bath, and BH₃·THF (23.0 mL, 230.0 mmol, 1.08 equiv) was added over a period of 60 min. The flask was sealed and the mixture was left stirring at 0 °C until full conversion of the starting material was detected by TLC (30 min).

The light-yellow solution was carefully treated with H₂O (20 mL), followed by neutralization with 25% NH₄OH. The solvents were removed under vacuum and the residue was adsorbed on Celite (24 g, suspension in MeOH). Purification by column chromatography (cyclohexane–EtOAc, 15:1, 10:1, 8:1, 6:1, 300 g silica gel, size: 13 × 7.5 cm); yield: 8.61 g (20.6 mmol, 97%); yellow, very viscous liquid.

HR-MS (DI-EI): m/z [M]+ calcld for C₁₆H₁₇NO₂: 255.0, found: 255.1259.
IR (ATR): 3342, 2946, 2859, 1730, 1681, 1591, 1571, 1499, 1435, 1404, 1372, 1314, 1215, 1188, 1140, 1081, 1042, 807, 788, 697, 644, 562, 520 cm⁻¹.

1H NMR (300 MHz, CDCl₃): δ = 8.16 (d, J_HH = 2.0 Hz, 1 H, ArH), 7.93 (d, J_HH = 7.0 Hz, 1 H, HH), 7.53 (dd, J_HH = 8.9 Hz, J_HH = 1.6 Hz, 1 H, ArH), 6.57 (d, J_HH = 9.0 Hz, 1 H, ArH), 3.94–3.62 (m, 7 H, 2 × CH₃, CH), 2.78–2.62 (m, 1 H, CH₂), 2.13–1.92 (m, 2 × CH₃, CH), 1.90–1.51 (m, 7 H, CH₃).

13C NMR (75.53 MHz, CDCl₃): δ = 175.9 (C₆), 168.2 (C₅), 149.6 (C₄), 142.8 (CH₃om), 140.1 (CH₁om), 114.3 (CH₃om), 112.1 (C₁), 73.9 (C₃), 51.8 (2 × CH₃), 46.9, 38.7, 32.5, 31.0, 28.1, 21.2.

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Supporting Information

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