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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1021/acs.jpca.5b02809>

The Journal of Physical Chemistry A, 119, 25, pp. 6703-6713, 2015-06-01

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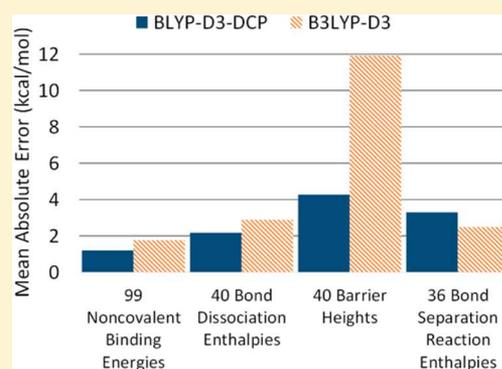


Dispersion Corrections Improve the Accuracy of Both Noncovalent and Covalent Interactions Energies Predicted by a Density-Functional Theory Approximation

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S Supporting Information

ABSTRACT: The use of pairwise dispersion corrections together with dispersion-correcting potentials (DCPs) offers a computationally low-cost approach to improving the performance of a density-functional theory based method with respect to the prediction of important chemical properties. In this work, we develop DCPs for the C, H, N, and O atoms for use with the BLYP generalized gradient approximation functional coupled with “D3” pairwise dispersion corrections and 6-31+G(2d,2p) basis sets. The combined approach, referred to as BLYP-D3-DCP, offers generally improved performance over both unadorned BLYP and BLYP with D3 corrections with respect to the prediction of noncovalent binding energies (BEs) and covalent bond dissociation enthalpies (BDEs). Predicted barrier heights for a set of pericyclic and Diels–Alder reactions are improved in some instances, as are organic bond separation reaction energies and radical stabilization energies. It is also shown that the BLYP-D3-DCP approach outperforms B3LYP-D3 in the prediction of many chemical properties, in particular noncovalent BEs and BDEs, suggesting that the addition of D3 and DCP corrections, which have negligible computational cost, to simple density functionals like BLYP may elevate their performance to that of more complex functionals such as B3LYP.



INTRODUCTION

Approximations to density-functional theory (DFT)^{1,2} have revolutionized computational chemistry and physics because they are able to predict fairly accurate physical properties for a wide range of systems. At the core of the success of DFT approximations is the low computational cost versus the accuracy of properties they predict. Whereas highly accurate wave function theory methods scale with the number of electrons, N , as $N^5 - N^7$, “simple” DFT-based methods scale formally as N^3 . One consequence of the lower scaling of DFT-based methods is that they are capable of treating much larger systems that might not be feasible for most wave function theory approaches, including Hartree–Fock theory.³

The development of improved DFT methodologies has followed the path of systematic increases in the complexity of the exchange–correlation functional, E_{xc} . For example, the construction of E_{xc} that depends on the electron density and gradient (viz., “GGA” functionals) offered a significant improvement in accuracy of predicted chemical properties over the simpler local density approximation (LDA). This spawned the development of many different formulations of GGA functionals, for example BLYP,^{4,5} PBE,⁶ and BP86.^{4,7} Hybrid functionals increase the complexity of DFT-based

methods by mixing Hartree–Fock exchange into GGA functionals. Becke showed⁸ that hybrid functionals are superior to “pure” GGA methods when it comes to predicting thermochemical properties, and this gave rise to the popularity of the B3LYP approach. Bond dissociation enthalpies (BDEs) in particular can be well-predicted by hybrid functionals.^{9,10} More recently, range-separated hybrid functionals have been introduced (e.g., CAM-B3LYP,¹¹ LC- ω PBE^{12,13}), wherein the degree of admixture of Hartree–Fock exchange increases with increasing distances between electrons. The added complexity of hybrid and range-separate hybrid functionals generally results in increased calculation times relative to pure GGA functionals, which may be impactful when attempting to treat solid-state systems through the use of periodic plane wave approaches.¹⁴

Improvements in the ability of DFT-based methods to predict chemical properties like BDEs have been made in parallel with efforts to address the inability of conventional DFT approximations to accurately predict noncovalent interactions. Over the past decade, several interesting

Received: March 23, 2015

Revised: May 30, 2015

Published: June 1, 2015

approaches for resolving the “dispersion problem” in DFT have been put forward, many of which we have recently reviewed.¹⁵ Of particular interest for the present work is the empirical pairwise “D3” dispersion correction method of Grimme,¹⁶ wherein an energy correction for dispersion interactions, E_{disp} , between all pairs of atoms A and B separated by distance R_{AB} is described as follows:

$$E_{\text{disp}} = - \sum_{A>B} \left[\frac{C_6^{\text{AB}}}{R_{\text{AB}}^6} \right] f_6(R_{\text{AB}}) + s_8 \left[\frac{C_8^{\text{AB}}}{R_{\text{AB}}^8} \right] f_8(R_{\text{AB}}) \quad (1)$$

where C_6^{AB} and C_8^{AB} are dispersion coefficients determined by a Casimir–Polder-like equation using frequency-dependent polarizabilities calculated using a DFT-based method, and s_8 is a DFT method dependent scaling parameter. The damping functions f limit the range of the dispersion correction, and the form of the damping function proposed by Becke and Johnson^{17–19} has been shown to be superior to that used in the original D3 formulation.²⁰ We point out that Becke and Johnson have developed a rather elegant pairwise dispersion approach wherein the dispersion coefficients are determined from first-principles from the exchange-hole dipole moment.^{17–19} The pairwise correction approach to the introduction of dispersion is quite powerful because it adds little computational overhead to the underlying DFT-based method. The D3 approach is widely implemented in popular computational chemistry programs such as Gaussian.²¹

We have developed dispersion-correcting potentials (DCPs) to tackle the dispersion problem.^{22–25} DCPs are atom-centered Gaussian-type functions, identical in form to those used in effective-core potentials,²⁶ viz.:

$$U_l(r) = r^{-2} \sum_{i=1}^{N_l} c_{li} r^{n_{li}} e^{-\xi_{li} r^2} \quad (2)$$

where l is the angular momentum, N_l is the number of Gaussian functions, n_{li} is the power of r (usually set to 2), c_{li} is the coefficient of the Gaussian and ξ_{li} is its exponent. Projection operators²⁷ associated with the different angular momenta allow the functions to introduce anisotropy into the effective potentials. The general idea behind this approach is that DCPs alter the potential in which the electron density of a system is constructed. This is achieved through a modification of the Hamiltonian formulated for the system under calculation, in the same way that is done when effective core potentials are employed. Although the development of DCPs originated out of our earlier work on quantum capping potentials,²⁸ they are similar to a plane wave-based technique introduced by von Lilienfeld et al.^{29–31} and the recent extension of Karalti et al.³² DCPs are completely empirical in that they are generated by optimizing the exponents and coefficients of a set of functions (eq 2) to minimize the error in a set of calculated properties. In connection to DCPs developed to correct for the dispersion problem, these properties include the binding energies (BEs) associated with the potential energy surfaces (PESs) of fitting sets composed of noncovalently interacting dimers. DCPs have been developed for the C, H, N, and O atoms for several functionals and basis sets^{22–25} and introduce very little additional computational cost to the DFT-based method with which they are used.

Although we showed that DCPs may exhibit some transferability between families of DFT approaches,^{22,23} and between different basis sets,²⁴ the best results are achieved

when DCPs are employed for the method and basis sets with which they were developed. Broader transferability between different basis sets can be achieved if DCPs are developed while mitigating basis set incompleteness errors through the use of counterpoise corrections, as demonstrated in ref 24.

An interesting aspect of DCPs is that they are able to improve the performance of DFT-based methods in predicting both noncovalent and covalent properties.²⁵ We recently demonstrated that the combination of DCPs with the LC- ω PBE functional results in an approach that is capable of predicting the BEs for a set of 109 noncovalently interacting dimers that constitute of the so-called S66, S22B, and HSG-A databases, *vide infra*, with a mean absolute error (MAE) of 0.24 kcal/mol. In comparison, the “unadorned” functional (i.e., the functional with no dispersion corrections) predicts the BEs for the 109 dimers with an MAE of 2.2 kcal/mol. The same LC- ω PBE-DCP approach also provides bond dissociation enthalpies for a set of 40 X–H and X–Y BDEs (X, Y = C, N, O) with an MAE of 1.6 kcal/mol, which is a factor of 2 reduction in MAE relative to the unadorned functional. We also showed in ref 25 that LC- ω PBE combined with D3 dispersion corrections also predict more accurate BEs and BDEs than the unadorned functional, but not to the extent of LC- ω PBE-DCP.

The possibility of improving the performance of computationally inexpensive DFT-based approaches for covalent and noncovalent properties using D3 and DCP is intriguing, despite the inherent empiricism associated with the corrections. One potentially interesting application in this connection is to improve the performance of a low cost DFT-based approach, e.g., a GGA functional such as BLYP, to the level of a higher-cost approach, e.g., a hybrid functional like B3LYP. von Lilienfeld explored this possibility in the context of using “force-correcting atom-centered potentials” to elevate the quality of BLYP-predicted harmonic frequencies of a series of small molecules to that of B3LYP.³³

In this paper, we present the results of our exploration of the use of DCPs with D3 corrections to provide a simple route to improve the general performance of a simple GGA functional, BLYP, with small basis sets. We undertook an approach whereby the D3 corrections would serve largely to improve noncovalent binding whereas the DCPs would be designed nominally to improve covalent binding as represented by BDEs. The small basis set was used with the notion that the outcome of our efforts may be a computational approach that is efficient and accurate enough to be applicable to large systems. A central theme of this effort is to determine whether or not it is possible to construct an approach that can produce results that are competitive with hybrid functionals at the computational cost of a GGA functional.

■ COMPUTATIONAL APPROACH

Development of Dispersion-Correcting Potentials.

The DCPs presented in this work were developed for use with the BLYP functional, 6-31+G(2d,2p) basis sets and D3 dispersion corrections, that is, the BLYP-D3/6-31+G(2d,2p) method. DCPs are developed by optimizing c_{li} and ξ_{li} values for a set of functions (eq 2) for the H, C, N, and O atoms. We describe the combined approach as BLYP-D3-DCP/6-31+G(2d,2p). Note that, unlike pairwise dispersion corrections, DCPs are applied to individual atoms and therefore it is not a requirement that DCPs be developed for all elements in a chemical system of interest (*vide infra*).

Table 1. Systems Comprising the Fitting Sets for the Optimization of DCPs in This Work

atom	noncovalent BEs	covalent BDEs ^g
carbon and hydrogen	(CH ₄) ₂ , ^a (C ₂ H ₆) ₂ , ^a (C ₃ H ₈) ₂ , ^a slipped-parallel (C ₆ H ₆) ₂ , ^{b,c} T-shaped (C ₆ H ₆) ₂ , ^{b,d}	H ₂ C–H, HC–H, H ₃ C–CH ₃ , H ₃ CCH ₂ –H
oxygen	(CO ₂) ₂ , ^a (H ₂ CO) ₂ , ^a H ₂ O–HOH, ^a formic acid dimer ^a	H–O, HO–CH ₃ , HO–H, HO–OH
nitrogen	CH ₄ ⋯NH ₃ , ^a H ₃ N⋯HNH ₂ , ^a H ₃ N⋯NH ₃ , ^a (H ₃ CCN) ₂ , ^a formamide dimer, ^a π -stacked uracil–uracil, ^{b,e} hydrogen-bonded uracil–uracil ^{b,f}	H ₂ N–NH ₂ , H ₂ N–CH ₃ , H ₂ N–H

^aThe structural data and binding energies or bond dissociation energies were taken from the Supporting Information of ref 24.. ^bThe structural data and binding energies or bond dissociation energies associated were taken from the S66×8 data available at www.begdb.com and described in ref 36. ^cThe scale factor used for the PES is 0.9927. ^dThe scale factor used for the PES is 0.9862. ^eThe scale factor used for the PES is 0.9929. ^fThe scale factor used for the PES is 1.0166. ^gFrom ref 10, corrected for zero-point energy and vibrational contributions to enthalpy.

In the present case, we initiated optimizations using as a starting point the set of DCPs that were presented in refs 24 and 34 for the B3LYP functional and included additional functions as necessary. Our earliest work with DCPs indicated that density functionals from the same family (i.e., BLYP and B3LYP) have optimal DCP functions with similar coefficients and exponents.^{22,23} However, in the present case the inclusion of dispersion corrections via D3 suggested to us that the associated DCPs will likely have much smaller coefficients, and so we scaled down the coefficients associated with the set of initial DCP guess functions by an order of magnitude. The DCPs functions were then optimized by minimizing the mean absolute error (MAE) in the BLYP-D3-DCP predicted BEs along the one-dimensional PES for a small set of noncovalently bonded dimers and a small number of representative BDEs, relative to reference data, and according to

$$\text{MAE} = \frac{1}{M} \sum_{j=1}^M \left(\frac{1}{N_j} \sum_{i=1}^{N_j} |B(D)E_i^{\text{ref}} - B(D)E_i^{\text{DCP}}| \right) \quad (3)$$

In eq 3, N_j is the number of data points associated with each BDE or PES in the fitting set, M is the number of entries in the fitting set, and $B(D)E_i^{\text{ref}}$ and $B(D)E_i^{\text{DCP}}$ represent the binding energies or the bond dissociation energies obtained from a reference or calculated using DCPs, respectively.

In the DCP optimizations, each BE is evaluated as the difference between the single-point electronic energy of a dimer and its rigid monomers and these values are compared to ab initio reference values obtained using CCSD(T) with extrapolations to the complete basis set (CBS) limit, which were obtained using an approach described by us previously,³⁵ or by Rezáč et al.³⁶ In cases where PESs were taken from the so-called S66×8 database of ref 36, we scaled (see footnotes of Table 1) the BEs to match the BEs at the PES minima to values calculated at a higher-level of theory by Rezáč et al. in a separate work.³⁷ BDEs were evaluated from the difference between the single-point energies of the parent molecules and the radicals formed following scission of indicated bonds. BDEs were compared to experimental values that were compiled in ref 10 and back-corrected for zero-point and enthalpic contributions to give bond dissociation energies. The systems used in the fitting of the DCPs are listed in Table 1.

The fitting data associated with optimization varies depending on which properties require improvement at a given stage of DCP development. Typically, the first stages of DCP optimizations are focused on BEs because most GGA

functionals are overly repulsive for most noncovalent interactions, especially dispersion.³⁸ However, because the DCPs in this work were designed *a priori* with the inclusion of the D3 dispersion correction, we focused our initial optimization on BDEs. It was necessary in later steps of the DCP optimization process to refine them to adequately reproduce BEs for three reasons: (i) DCPs optimized for the purpose of improving covalent binding properties will also modify noncovalent binding properties, (ii) there is room for improvement in the noncovalent BEs predicted using BLYP-D3, and (iii) D3 dispersion corrections were designed for use with complete basis sets and we use 6-31+G(2d,2p) in this work in the interest of developing a computationally economical approach. DCPs can, to some extent, mitigate the effects of incomplete basis sets.

The C and H DCP optimizations were performed simultaneously. The optimized C and H DCPs were then held constant and used, where applicable, for the O DCP optimizations, after which the N DCP optimizations were performed while keeping the C, N, and O DCPs fixed. The final steps in the optimizations involved collapsing multiple functions having nearly identical exponents into single functions and running several cycles of optimization on all of the DCPs simultaneously.

Our previous work on DCPs suggests that there are likely a small number of local minima in the parameter space associated with the potentials. There is no way to be certain that the DCPs we generate produce the lowest MAEs in conjunction with eq 3. However, initiating DCP optimizations from several different parameter starting points often results in a set of DCPs that have converged to roughly the same performance.

The DCP optimizations were performed using a set of scripts that handled job submissions and data processing. Gaussian-09²¹ was used to compute the BLYP-D3-DCP energies in all cases. Although we demonstrated that it is possible to develop basis sets that optimally balance calculation time and accuracy of the calculation of noncovalent BEs,³⁹ we chose to develop DCPs for use with standard 6-31+G(2d,2p) basis sets (employing d-functions with five primitives) to facilitate DCP development and application. As the same results will not be achieved using the present DCPs with different basis sets, and in the interest of applicability, we also developed BLYP-D3 DCPs for use with 6-31+G(d,p) and 6-31G(d) basis sets. The Supporting Information contains information about the DCPs developed for these smaller basis sets. Note that we do not

make use of corrections for basis set incompleteness in this work.

Testing of BLYP-D3-DCP. A number of benchmark databases were used to evaluate the performance of BLYP-D3-DCP/6-31+G(2d,2p) for noncovalent BEs. All of the noncovalent BEs reported in this work are compared to reference values that were generally obtained from high-level wave function theory calculations. We used the so-called S66 set originally formulated by Rezáč et al.,³⁷ which contains 23 dimers bound primarily by one or more hydrogen bonds, 23 dimers bound by primarily by dispersion/ π -stacking interactions, and 20 dimers bound by a mix of electrostatic and dispersion interactions. (Note that a small number of the constituents of the S66 set were used to fit the DCPs; see Table 1.) We recently computed refined BEs for the 23 hydrogen bonded dimers of the S66 set,⁴⁰ and these are used in the benchmarks for the present work. We further employed the HSG-A database, which was originally developed by Faver et al.,⁴¹ and refined by Marshall et al.⁴² This set of noncovalently bound dimers and trimers is composed of 21 neutral and charged fragments obtained from the HIV-II protease crystal structure having a bound inhibitor molecule, indinavir.

To assess the performance of the BLYP-D3-DCP approach for larger noncovalently bonded systems, we applied it to the S12L benchmark set of Grimme.⁴³ The S12L set contains two “tweezer” complexes with tetracyanoquinone (TCNQ) and 1,4-dicyanobenzene (complexes 2a and 2b); two “pincer” complexes with heteroatomic organic π systems (complexes 3a and 3b); a “buckycatcher” complexed with the fullerenes C60 and C70 (complexes 4a and 4b); an amide macrocycle bound to benzoquinone and glycine anhydride (complexes 5a and 5b); complexes of the cucurbit[6]uril cation with butylammonium and propylammonium (complexes 6a and 6b); and last, complexes of cucurbit[7]uril with the dicationic bis(trimethylammoniomethyl)ferrocene and the neutral 1-hydroxyadamantane (complexes 7a and 7b). For this set, Grimme corrected experimentally determined binding free energies for solvent and molecular vibration effects. Recently, Ambrosetti et al.⁴⁴ refined some of the energies in the S12L set using a quantum Monte Carlo approach, and we use these refined BEs for our evaluation purposes.

All of the benchmark calculations for noncovalent BEs involve single-point energy evaluations. We selected some representative members of the S66 set for the purpose of exploring the quality of the PESs predicted using BLYP-D3-DCP. The structures associated with the PESs were obtained from the S66 \times 8 database of Rezáč et al.³⁶

The performance of BLYP-D3-DCP/6-31+G(2d,2p) for covalent properties was assessed by computing the homolytic BDEs for a subset of species described in ref 10. BDEs were evaluated by calculating the enthalpy differences between parent molecules and their constituent radical species. For these evaluations we performed full geometry optimizations and frequency calculations at the BLYP-D3-DCP/6-31+G(2d,2p) level of theory. The calculated BDEs were compared directly to the experimental BDEs compiled in ref 10.

A broader investigation of thermochemical properties was explored utilizing some of the subdatabases of the extensive GMTKN30 database recently compiled by Goerigk et al.^{45,46} The large database is a compilation of high-level theoretical results for properties such as reaction barrier heights, reaction energies, and intra- and intermolecular noncovalent interactions for a large number of literature sources. The GMTKN30

database provides a convenient means for evaluating the performance of computational chemistry methods using a wide range of metrics. We used the BHPERI (barrier heights for pericyclic reactions),^{47–50} DARC (Diels–Alder reaction energies),⁵¹ BSR36 (bond separation energies of saturated hydrocarbons),⁵² and RSE43 (radical stabilization energies of organic molecules).⁵³

In recent work by Savin and Johnson,⁵⁴ it was demonstrated that common statistics used in judging density-functional approximations can lead to erroneous conclusions. This is because measures such as mean absolute errors (MAE) are strongly influenced by the size of a benchmark set. We include uncertainties with the MAE statistical analysis of our broader comparisons between the BLYP-D3-DCP and B3LYP-D3 approaches. As per ref 54, uncertainties in MAE are calculated as σ/\sqrt{n} , where n represents the number of points of data. The absolute error for each point is determined by $x_i = |x_{\text{calc},i} - x_{\text{ref},i}|$, and the standard deviation, σ , is calculated from

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (4)$$

The inclusion of uncertainties serves as a useful measure of distribution of errors in a particular set, where large uncertainty indicates a large spread of errors.

For the noncovalent and covalent data described above, we evaluated for comparative purposes the performance of unadorned BLYP and of BLYP-D3 using 6-31+G(2d,2p) basis sets. We also considered the performance of B3LYP (unadorned and with D3 corrections) to provide some evidence of promise for elevating the performance of BLYP to that of B3LYP. All calculations utilized the Gaussian-09 package.²¹

RESULTS AND DISCUSSION

Optimized Dispersion-Correcting Potentials for BLYP-D3. The BLYP-D3 DCP parameters developed for use with 6-31+G(2d,2p) basis sets are listed in Table 2. Some of the basic characteristics of DCPs are as follows: Functions with negative coefficients act in an attractive manner to increase BEs, whereas those with positive coefficients act in a repulsive manner. Additionally, small exponent functions extend the potential further into space. The exponents associated with the DCPs in Table 2 tend to be larger than those of DCPs we have previously developed, and this reflects the fact that they more greatly impact electron density closer to the nuclei. In other words, the DCPs developed in this work more greatly impact covalent behavior than noncovalent behavior (*vide infra*).

To provide a specific demonstration of the effect of the application of DCPs on the PESs of noncovalently bonded systems, we present in Figure 1 the deviations from CCSD(T)/CBS binding energies along the two-dimensional PESs for three dimers from the S66 \times 8 database. Figure 1a shows the errors in PESs for the dispersion-bound slipped parallel benzene dimer, Figure 1b shows the benzenemethylamide NH– π bonded complex, and Figure 1c shows the hydrogen-bonded methanol dimer computed using BLYP/6-31+G(2d,2p) with and without D3 and DCPs augmentations. Note that the benzene dimer PESs formed part of the DCP fitting set. For the benzene dimer, unadorned BLYP/6-31+G(2d,2p) predicts an entirely repulsive PES. Application of the D3 correction produces a PES that is overbound by ca. 1.2 kcal/mol at the minimum but that otherwise has reasonable behavior out to twice the separation

Table 2. Optimized BLYP-D3/6-31+G(2d,2p) Dispersion-Correcting Potentials for the H, C, N, and O Atoms for Use without Counterpoise Corrections^a

atom	function type	function parameters		
		ζ_i	c_i	
H	P and higher	0.56609	-0.00100	
		0.74529	-0.00049	
		0.46956	0.00079	
	S-P	0.47241	-0.00391	
C	F and higher	0.44783	0.00083	
		0.26426	-0.00588	
		0.56629	0.00434	
	S-F	0.37867	0.00186	
			0.09208	0.01328
		P-F	0.66248	-0.00102
	D-F	0.18456	-0.00120	
N	F and higher	0.52429	0.00059	
		0.74898	-0.00001	
		0.26621	0.00031	
	S-F	0.28659	-0.00680	
	P-F	0.20443	-0.00934	
	D-F	0.66072	0.00177	
O	F and higher	0.20391	0.00059	
		0.44121	-0.00022	
		0.34620	-0.00001	
	S-F	0.18593	0.03085	
	P-F	0.26898	-0.00030	
	D-F	0.08529	-0.00034	

^aThe entries are given as angular momentum function type and the ζ_i and c_i values according to eq 2. Additional formatting of the listed potentials is required for use in computational chemistry packages; see the Supporting Information.

of the monomers in the minimum energy structure. It is evident from the results reported by Goerigk and Grimme⁴⁶ that the overbinding in Figure 1 is a consequence of basis set incompleteness because BLYP-D3 with very large basis sets produces a BE for slipped parallel benzene at the minimum that is underbound by only 0.03 kcal/mol. It was expected that the optimized C and H DCPs would counteract to some extent the BLYP-D3 overbinding and this indeed is the case: Near the minimum of the PES, the BLYP-D3-DCP are in close agreement with the reference PES, whereas at separations greater than 1.1 times the monomer separation at the minimum, the BLYP-D3-DCP PES coincides with that of BLYP-D3. Similar behavior to that described for the benzene dimer is observed in the examples of the benzenemethylamide and the methanol dimer PESs. We conclude from the behavior displayed in Figure 1 that the DCPs compensate to some extent for the effects of basis set completeness associated with the use of BLYP-D3/6-31+G(2d,2p) for the prediction of properties related to noncovalent binding. This is an interesting and potentially useful functionality of DCPs. We further conclude that the dissociation behavior associated with noncovalently bonded dimers introduced by the D3 corrections is preserved when coupled with DCPs.

It is worthwhile reiterating that DCPs do not act in the same manner as pairwise corrections and so it is possible for DCPs to be applied to a subset of atoms in a system with good effect.

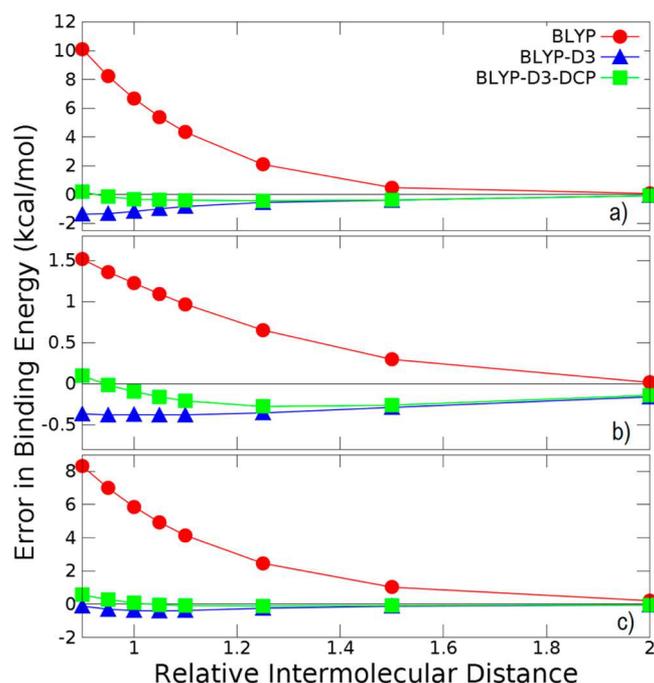


Figure 1. Deviation in binding energy relative to CCSD(T)/CBS along potential energy surfaces of the (a) π -stacked benzene dimer, (b) benzenemethylamide (N-H π) dimer, and (c) methanol dimer. The reference PES and the associated structures were obtained from the S66X8 set of ref 36. The reference PES energies were scaled according to the description provided in the previous section. The relative intermonomer distance is defined by the scaling factor applied to the intermonomer separation of the dimer minimum structure. All BLYP calculations utilized 6-31+G(2d,2p) basis sets. Negative error reflects overbinding. See the Supporting Information for additional information.

This principle is illustrated in Figure 2 on PESs for the benzene-neopentane dimer. As was observed for the dimer

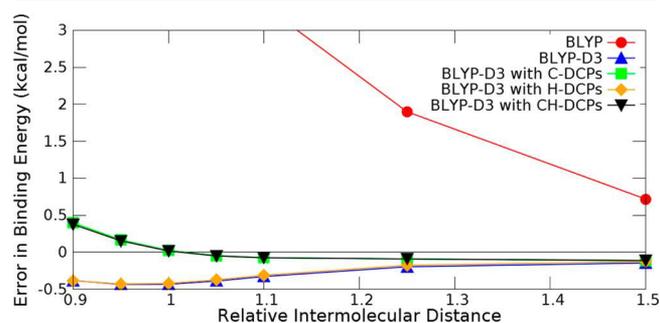


Figure 2. Deviation in binding energy relative to CCSD(T)/CBS along potential energy surfaces for the benzene-neopentane dimer computed with uncorrected and corrected BLYP/6-31+G(2d,2p). The reference PES energies came from ref 36 and were scaled according to the description provided in the previous section. Relative intermonomer distance is defined by the scaling factor applied to the intermonomer separation of the dimer minimum structure. Negative error reflects overbinding.

PESs plotted in Figure 1, BLYP-D3/6-31+G(2d,2p) without DCPs over binds, likely as a consequence of basis set incompleteness. Application of only H-DCPs to the BLYP-D3 treatment reduces the overbinding very slightly. Use of only C-DCPs with BLYP-D3/6-31+G(2d,2p) has a noticeable

Table 3. Summary of Performance on the S66 Benchmark (Sub)set for Unadorned BLYP/6-31+G(2d,2p), with D3-Correction, and with D3-DCPs^a

benchmark set	BLYP		BLYP-D3		BLYP-D3-DCP	
	MAE/MSE	MAPE/MSPE	MAE/MSE	MAPE/MSPE	MAE/MSE	MAPE/MSPE
S66 - hydrogen bonded subset	2.09/2.09	26.9/26.9	0.37/−0.32	4.8/−4.0	0.30/−0.12	4.1/−1.6
S66 - dispersion subset	5.70/5.70	171/171	0.57/−0.57	16.7/−16.7	0.16/−0.06	4.5/−1.4
S66 - mixed interactions subset	3.48/3.48	97.5/97.5	0.28/−0.25	8.5/−7.8	0.17/0.08	4.8/1.8
S66 set - overall	3.77/3.77	104/104	0.41/−0.39	10.3/−9.8	0.21/−0.03	4.4/0.3
uncertainty in MAE for overall set	0.26		0.04		0.04	

^aValues are in kcal/mol except percent values. Negative values reflect overbinding. Full data are listed in the Supporting Information.

Table 4. Signed Errors in Binding Energies (SE) Calculated for the Noncovalently Bonded Dimers of the HSG-A Benchmark Set, Relative to High-Level Values, Using BLYP/6-31+G(2d,2p) with Pairwise Dispersion Correction and Dispersion-Correcting Potentials (D3-DCPs), the D3 Correction without DCPs (D3), and BLYP with No Dispersion Corrections at All (Unadorned)^a

complex	HSG-A name	high-level value ^b	D3-DCP ^c	D3 ^c	unadorned ^c
methane- <i>N</i> - <i>tert</i> -butylformamide	ala29-big	−0.518	0.157	0.019	2.097
ethane-indan-2-ol	ala128-small	−2.283	0.068	−0.243	3.723
benzene- <i>N</i> -methylguanidine (H ⁺) ^d	arg8	−2.478	−0.736	−0.893	3.199
acetate ion-water-acetic acid	ash26-asp125	−16.526	1.775	0.899	4.974
3-(acetylamino)propionate ion-methanol	asp129-big	−19.076	0.571	0.028	3.820
benzene-acetate ion	asp130	−5.998	0.170	−0.050	1.920
(dimethylamino)methanol-2-FAA ^e	gly28-big	−3.308	0.077	−0.110	3.251
pyridine-2-(formylamino)acetamide	gly50-ring-big	−0.581	−0.029	−0.289	2.756
<i>N</i> -methylacetamide-2-FAA	gly50-v1	−5.066	−0.125	−0.248	1.963
<i>N</i> -methylacetamide- <i>N</i> -methylacetamide	gly127	−7.509	0.255	0.072	3.376
<i>N</i> -methylacetamide-2-FAA	gly148	−6.274	0.219	0.035	2.653
propane- <i>N</i> - <i>tert</i> -butylformamide	ile48-big	0.302	−0.080	−0.225	2.464
butane-benzene	ile147	−2.103	−0.063	−0.334	3.543
butane- <i>N</i> - <i>tert</i> -butylformamide	ile150-big	−1.378	−0.008	−0.265	4.344
ethane-ethane-1,2-diamine	ile184	−0.856	0.129	−0.017	2.234
toluene-2-methylpropane	leu23-big	−1.100	0.007	−0.083	1.659
ethane-3-methylpyridine	pro181	−1.534	0.025	−0.287	3.775
ethane- <i>N</i> - <i>tert</i> -butylformamide	val33-big	−0.472	0.027	−0.134	2.459
propane-benzene	val83	−1.598	0.136	−0.236	3.567
propane-benzene	val132	0.378	0.271	0.021	2.945
acetate ion-water- <i>N</i> -methylacetamide	wat200	−9.538	0.059	−0.080	1.788
mean absolute/signed error			0.24/0.14	0.21/−0.11	2.98/2.98
mean absolute/signed % error			11.0/4.6	14.5/6.3	237/237

^aOverall performance statistics for the set are provided at the bottom of the table. All data are in kcal/mol except percent values. Negative values of SE reflect overbinding. ^bTaken from ref 42. ^cSigned errors defined as BE(DFT) − BE(high-level value). ^dProtonated *N*-methylguanidine. ^e2-(Formylamino)acetamide.

reduction in the overbinding and brings the PES into much better agreement with the CCSD(T) PES, with a slight additional improvement found for the full BLYP-D3-DCP treatment.

Performance of BLYP-D3-DCP on Noncovalently Interacting Systems. In Table 3 we summarize the errors of the BEs predicted for the members of the S66 set of noncovalently bonded dimers using BLYP-D3-DCP in comparison with BLYP-D3 and unadorned BLYP, all with 6-31+G(2d,2p) basis sets. Table S1 in the Supporting Information contains all of the calculated BEs for the S66 set.³⁷

On average, the BLYP-D3-DCP method slightly overbinds the dimers of the S66 set, with a mean signed error (MSE) of −0.03 kcal/mol for all 66 entries. The bulk of the overbinding comes from the hydrogen bonded dimer subset (MSE = −0.12 kcal/mol), with a smaller contribution from the dispersion-bound subset (MSE = −0.06 kcal/mol). The dimers interacting via mixed noncovalent interactions are, on average, under-

binding as indicated by an MSE of 0.08 kcal/mol. The BLYP-D3/6-31+G(2d,2p) BEs, on the other hand, are on average strongly overbinding with an MSE of the entire S66 set of −0.39 kcal/mol. This can be compared to the mean signed deviation reported by Goerigk et al. in the Supporting Information of ref 20 of −0.10 kcal/mol obtained using BLYP-D3/def2-QZVP, and this emphasizes that the use of 6-31+G(2d,2p) basis sets in the present work results in overbinding errors as a consequence of basis set incompleteness. Because DCPs reduced the overbinding when used with BLYP-D3/6-31+G(2d,2p), we conclude that the DCPs mitigate to a good extent the effects of basis set incompleteness.

The mean absolute error (MAE) in BEs is commonly used to assess the quality of prediction made by dispersion-corrected DFT methods. For BLYP-D3-DCP/6-31+G(2d,2p), we find an MAE of 0.21 kcal/mol and an MAE of 0.41 kcal/mol for BLYP-D3/6-31+G(2d,2p). These compare to an MAE of 0.19 kcal/mol for BLYP-D3/def2-QZVP, as reported in ref 20, again

indicating that DCPs provide a promising strategy for mitigating some of the effects of basis set incompleteness in the treatment of noncovalent interactions. We also note that BLYP-XDM/aug-cc-pVTZ also predicts an MAE of 0.19 kcal/mol.⁵⁵ Overall, the performance of BLYP-D3-DCP/6-31+G(2d,2p) is highly competitive with other dispersion-corrected DFT-based methods when it comes to predicted the BEs of the S66 set.¹⁵ Not surprisingly, unadorned BLYP/6-31+G(2d,2p) predicts an MAE for the S66 set that is an order of magnitude larger than the dispersion-corrected values.

We thought it might be interesting to apply our DCPs to the BLYP-XDM approach to understand the transferability characteristics of the DCPs to other pairwise dispersion corrections. No XDM parameters were available for 6-31+G(2d,2p) basis sets so we tested our DCPs using XDM parameters for a series of basis sets for which we were able to obtain parameters.⁵⁶ The resulting MAEs for the BEs in the S66 were found to be 0.36, 0.41, and 0.33 kcal/mol using BLYP-XDM-DCP/6-31+G(2d,2p) with XDM parameters optimized for the 6-31+G(d,p), aug-cc-pVDZ, and aug-cc-pVTZ basis sets, respectively. We conclude from this exercise that transferability of our DCPs between D3 and XDM is moderate and that we can likely achieve good improvement through the use of XDM parameters optimized for use with 6-31+G(2d,2p) basis sets and/or if the DCP parameters were optimized with XDM parameters directly.

Table 4 shows the performance of BLYP-D3-DCP, BLYP-D3, and unadorned BLYP for predicting the BEs in the HSG-A benchmark set. The performance of BLYP-D3-DCP/6-31+G(2d,2p) is generally very good with MAE and MSE of 0.24 and 0.14 kcal/mol, respectively. The acetate ion–water–acetic acid complex is poorly treated and has a high SE of 1.78 kcal/mol (underbinding). We are not able to explain this poor treatment of acetate ion–water–acetic acid complex but we do not believe the error to reveal a pathological deficiency with DCPs because B3LYP-DCP performs reasonably well for this complex.²⁴ BLYP-D3/6-31+G(2d,2p) performs slightly better without the inclusion of DCPs when MAE and MSE are as metrics, but the opposite is true if mean absolute percent errors (MAPE) and mean signed percent errors are considered (see bottom of Table 4). The performance of the unadorned BLYP/6-31+G(2d,2p) is very poor with and MAE of 2.98 kcal/mol (237%).

The performance of BLYP-D3-DCP on the large systems comprising the S12L set of Grimme,⁴³ is demonstrated in Table 5. Complexes 3b and 7a contains atoms for which DCPs have not been developed (chlorine and iron, respectively). In all cases involving members of the S12L set, we applied C, H, O, and N DCPs to their respective atoms only. We previously pointed out that the omission of DCPs for these atoms is expected to have very little, if any, effect on calculated binding energies.²⁵ This is especially true in the case of complex 7a where the iron atom is complexed in the ferrocene moiety. Furthermore, we showed in Figure 2 that it is unnecessary to apply DCPs to the entirety of a system to benefit from their use.

Unadorned BLYP/6-31+G(2d,2p) performs extremely poorly for the S12L set, giving an MAE (MSE) in BEs of 31.2 kcal/mol and an MAPE of more than 100. The poor result reflects the significant underbinding that is typical for GGA DFT methods with no dispersion corrections. Inclusion of D3 dispersion correction increase binding considerably, reducing the MAE to 11.8 kcal/mol, net overbinding. A large part of this

Table 5. Signed Errors in Binding Energies (SE) Calculated for the Noncovalently Bonded Dimers of the S12L Benchmark Set, Relative to High-Level Values, Using BLYP/6-31+G(2d,2p) with Pairwise Dispersion Correction and Dispersion-Correcting Potentials (D3-DCPs), the D3 Correction without DCPs (D3), and BLYP with No Dispersion Corrections at All (Unadorned)^a

complex ^b	high-level value ^b	D3-DCP ^c	D3 ^c	unadorned ^c
2a ^d	-27.2	-8.8	-13.6	37.7
2b ^d	-17.2	-6.5	-10.1	27.1
3a	-24.3	-5.7	-9.9	32.0
3b	-20.4	-2.9	-4.6	18.1
4a ^d	-25.8	-17.8	-25.6	47.7
4b	-28.7	-18.2	-26.3	51.5
5a ^d	-33.4	-3.2	-6.3	26.1
5b	-21.3	-4.3	-7.1	22.7
6a ^d	-81.0	-7.1	-7.7	24.8
6b	-77.0	-6.7	-7.2	20.1
7a	-131.5	-9.3	-11.5	57.5
7b ^d	-24.1	-9.6	-11.1	34.4
mean absolute/ signed error		8.4/-8.4	11.8/-11.8	31.2/31.2
mean absolute/ signed % error		27.9/-27.9	40.8/-40.8	109/109

^aOverall performance statistics for the set are provided at the bottom of the table. All data are in kcal/mol except percent values. Negative values of SE reflect overbinding. ^bSee text and ref 43 for additional details related to the nature of the complexes. ^cSigned errors defined as BE(DFT) – BE(high-level value). ^dBE obtained from ref 44.

MAE is likely due to a contributions due to basis set incompleteness, as suggested by an MAE of ca. 4 kcal/mol reported by Risthaus and Grimme for BLYP-D3/QZVP.⁵⁷ Note that the value reported in ref 57 includes corrections for three-body interactions, which reduces binding errors by an average of 2.2 kcal/mol. This suggests that BLYP-D3/QZVP in the absence of the three-body correction would predict an MAE of ca. 6.2 kcal/mol for the S12L set. When combined with BLYP-D3, DCPs reduce the overbinding on the S12L set to give an MAE of 8.4 kcal/mol. This level of performance is comparable to BLYP-D3/QZVP without three-body corrections but is not competitive with other dispersion-corrected methods. In fact, even DCPs developed for use with LC- ω PBE and B3LYP perform much better than the BLYP-D3-DCP approach presented in this work, giving MAEs of 3.4²⁵ and 2.6 kcal/mol,²⁴ respectively.

Performance of BLYP-D3-DCP on Bond Dissociation Enthalpies. In part, the value of a computation chemistry method can be assessed according to its ability to accurately predict the outcome of chemical reactions that are thermodynamically controlled. In this connection, BDEs represent an important chemical property. We applied the BLYP-D3-DCP approach, along with the BLYP-D3 and unadorned BLYP methods with 6-31+G(2d,2p) basis sets to assess their ability to predict the BDEs of a set of 40 bonds for which the experimental values were compiled in ref 10. The bonds contain X–H and X–Y (X, Y = C, N, O) moieties and are representative of simple, common organic molecules with a broad range of BDEs. The results are summarized in Table 6 and presented in their entirety in Table S2 of the Supporting Information.

Table 6. Summary of Performance on the BDE Benchmark (Sub)set for Unadorned BLYP/6-31+G(2d,2p), with D3-Correction, and with D3-DCPs^a

set	BLYP		BLYP-D3		BLYP-D3-DCP	
	MAE/MSE	MAPE/MSPE	MAE/MSE	MAPE/MSPE	MAE/MSE	MAPE/MSPE
BDE X-H subset	4.4/−4.4	4.4/−4.4	3.8/−3.8	3.8/−3.8	2.1/−1.9	2.3/−2.1
BDE X-Y subset	6.9/−6.9	9.4/−9.4	4.7/−4.9	6.2/−6.2	2.0/−1.5	2.5/−2.0
BDE overall set	5.3 ^b /−5.4	6.3/−6.1	4.0 ^c /−3.9	4.8/−4.5	2.2 ^d /−1.4	2.3/−2.0

^aValues are in kcal/mol except percent. Negative values reflect underestimated bond dissociation enthalpies. Full data are listed in the Supporting Information. ^bUncertainty in MAE (kcal/mol) is 0.4. ^cUncertainty in MAE (kcal/mol) is 0.3 and. ^dUncertainty in MAE (kcal/mol) is 0.3.

Unadorned BLYP/6-31+G(2d,2p) almost uniformly underestimates the BDEs listed in Table S2 (Supporting Information). The sole exception is the O–O bond in hydrogen peroxide. For C–H, O–H, and N–H bonds, the MSEs predicted by BLYP/6-31+G(2d,2p) are −3.7, −4.0, and −4.4 kcal/mol, respectively. MSEs in X–Y bonds (X, Y = C, N, O) are roughly twice as large, ranging from −7.0 kcal/mol for C–C scissions to −8.4 kcal/mol for C–N bonds. Overall, BLYP/6-31+G(2d,2p) underestimates the BDEs in the entire set of bonds with an SE of −5.4 kcal/mol (ca. −6.1%). This underestimation of BDEs is a common shortcoming of many DFT-based methods.

One prominent cause for the underestimation in BDEs is delocalization error, which is problematic in density functionals containing little or no Hartree–Fock exchange.⁵⁸ Delocalization error tends to differentially stabilize radicals relative to parent molecules, thereby underestimating BDEs. The impact of this error is clear from the data presented in Table S2 (Supporting Information) where the parent molecules associated with radicals with localized unpaired electrons have the smallest signed errors in BDE (e.g., H₃C–H SE = −0.7 kcal/mol) whereas the molecule associated with highly delocalized radicals have large signed errors in BDE (e.g., (H₃C)₂CH–H SE = −7.4 kcal/mol). In any case, the BLYP/6-31+(2d,2p) errors in BDE are sufficiently large that the unadorned method offers limited predictive value for simulations involving the thermochemistry of simple organic species.

The inclusion of dispersion corrections through the use of D3 improves BDEs almost uniformly (again, the sole exception is associated with HO–OH). This improvement is expected on the basis that unadorned BLYP/6-31+G(2d,2p) underestimates BDEs and on the basis that pairwise dispersion corrections differentially stabilize the larger molecular species over the two smaller radical fragments. This can be easily understood by considering the simplest bond dissociation case of a diatomic molecule. The molecular energy of the diatomic will be lowered through the inclusion of a pairwise correction for dispersion whereas there is no energy lowering of the atomic energies due to dispersion because the atoms are infinitely separated in space. From this example it is easy to understand how the inclusion of dispersion through pairwise corrections always contributes to an increase in BDE. (A similar illustration can be used to understand that pairwise dispersion will always lower the calculated barrier heights for bimolecular reactions.) Given the behavior of pairwise dispersion corrections, there is also an expectation that the nature of the bond scission process will impact the magnitude of the contribution the corrections will make to BDEs, viz., smallest for X–H bonds and largest for X–Y bonds where X and Y are large fragments. These expectations are supported by the data displayed in Table S2 (Supporting Information). Ultimately, BLYP-D3/6-31+G(2d,2p) improves

X–H and X–Y BDEs over the unadorned functional by an average of 0.6 and 2.0 kcal/mol, respectively.

The inclusion of DCPs in the treatment of BDEs results in a substantial improvement over the results obtained with BLYP-D3 and unadorned BLYP. The overall performance of BLYP-D3-DCP/6-31+G(2d,2p) for X–H BDEs is reflected by an MAE of 2.1 kcal/mol, which is less than half of the unadorned functional. The performance for X–Y bonds is even better, where the BLYP-D3-DCP approach gives an MAE of 2.0 kcal/mol, and this is almost 3.5 times lower than the MAE obtained with unadorned BLYP. The degree of improvement in BDEs over BLYP-D3 and unadorned BLYP is consistent with what we were able to achieve with DCPs designed for use with the LC- ω PBE functional. The LC- ω PBE-DCP/6-31+G(2d,2p) approach gave an MAE of 1.6 kcal/mol for the same set of X–H and X–Y bonds, whereas unadorned LC- ω PBE gave an MAE of 3.2 kcal/mol.²⁵ Therefore, for BDEs we are able to achieve with a simple GGA functional a level of performance on par with that of a complex, range-separated functional.

SUMMARY AND OUTLOOK

Can DCPs elevate the performance of BLYP to that of B3LYP? This is a question that was posed in the Introduction. As computational chemistry methods are applied to increasingly larger systems, the question of their efficiency—in particular,

Table 7. Mean Absolute Errors with Uncertainty (MAE, kcal/mol) and Mean Absolute Percent Errors (MAPE) in Binding Energies and Bond Dissociation Enthalpies for Various Benchmark Sets Obtained with DFT/6-31+G(2d,2p)

benchmark set/ subset	BLYP-D3-DCP		B3LYP-D3	
	MAE(uncertainty)	MAPE	MAE(uncertainty)	MAPE
S66/hydrogen bonding	0.30 (0.08)	4.1	0.75 (0.08)	8.8
S66/dispersion	0.16 (0.05)	4.5	0.57 (0.06)	16.4
S66/mixed interactions	0.17 (0.04)	4.8	0.42 (0.04)	12.5
S66 total	0.21 (0.04)	4.4	0.58 (0.04)	12.6
HSG-A	0.24 (0.10)	11.0	0.28 (0.04)	17.9
S12L	8.4 (1.5)	27.9	10.9 (1.4)	35.8
BDE/X–H bonds	2.1 (0.4)	2.3	2.3 (0.3)	2.2
BDE/X–Y bonds	2.0 (0.5)	2.4	4.1 (0.5)	5.1
BDE total	2.2 (0.3)	2.3	2.9 (0.3)	3.5
BHPERI	3.0 (0.5)	17.1	1.5 (0.3)	8.5
DARC	6.7 (1.1)	28.7	31.2 (5.4)	129
BSR36	3.3 (0.3)	23.1	2.5 (0.3)	17.1
RSE43	3.5 (0.3)	119	1.9 (0.2)	65.3

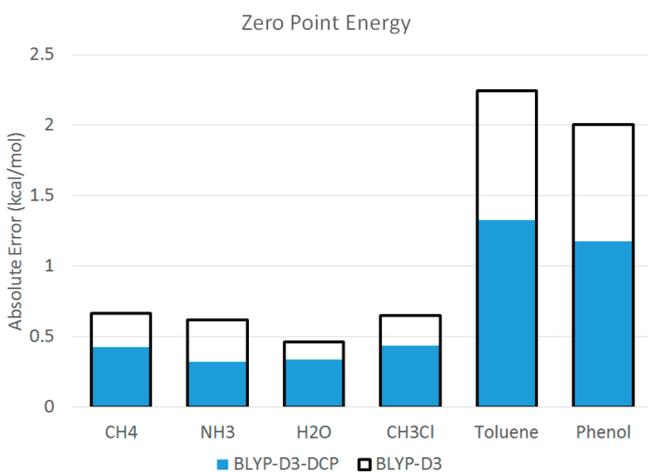


Figure 3. Absolute error (kcal/mol) in predicted zero-point energies (ZPE) for a series of representative organic molecules. The errors were evaluated as the difference between the ZPE determined using B3LYP-D3 and those obtained using either BLYP-D3 or BLYP-D3-DCP. In all cases, 6-31+G(2d,2p) basis sets were used. Note that the D3 corrections themselves do not affect ZPEs.

with respect to run time—becomes critical. Formally, GGA functionals like BLYP scale as N^3 with system size (with N being the number of electrons), whereas hybrid functionals scale with N^4 .³ Therefore, low-cost corrections such as D3 and DCP that may elevate the performance of BLYP to that of B3LYP or better may be of value. To examine this possibility, we present in Table 7 a summary of some of the performance statistics for BLYP-D3-DCP/6-31+G(2d,2p) for the benchmark sets described above and compare these to statistics obtained using B3LYP-D3/6-31+G(2d,2p). We also conducted additional performance assessments of the two methods on the BHPERI, DARC, BSR36, and the RSE43 databases. We use D3 corrections with B3LYP for our comparison because D3 has a computational cost that is negligible relative to that of the underlying DFT method and because D3 corrections (or similar) are required to predict noncovalent interactions that are reasonable. It is worthwhile restating that D3 corrections that were designed for use with B3LYP were also designed for use with nearly complete basis sets. The corrections nevertheless improve the performance of “small basis set” B3LYP, as has been shown in the past, in particular for the treatment of noncovalent interactions.²⁴

The binding energies of noncovalently interacting small molecules as represented by the S66 and HSG-A databases are predicted to be better on average by BLYP-D3-DCP/6-31+G(2d,2p) than by B3LYP-D3/6-31+G(2d,2p). With respect to the S66 database, the errors in the hydrogen bonding, dispersion, and mixed interactions subsets are factors of 2.5–3.6 larger for B3LYP-D3 than for BLYP-D3-DCP. However, the errors associated with the BEs in the HSG-A database for the two methods are comparable, with MAE results that overlap within the calculated uncertainties. For large noncovalently bonded systems as represented by the S12L set, BLYP-D3-DCP performs somewhat better than B3LYP-D3, giving an MAE that is ca. 2.5 kcal/mol lower than the hybrid method, but this difference is smaller than the sum of the uncertainties on the two MAE values. In any case, neither method can be considered to perform at an acceptable level for the S12L set. Nevertheless, both methods may find some general utility in the treatment of large molecular complexes.

Within the calculated level of uncertainty, BLYP-D3-DCP performs as well as B3LYP-D3 for X-H BDEs. We showed some time ago that B3LYP performs particularly well in this connection,⁵⁹ and so the level of performance of BLYP-D3-DCP for these bonds is encouraging. B3LYP is known to perform less effectively for X–Y bonds⁶⁰ and this is reflected in the MAE of 4.1 kcal/mol obtained using B3LYP-D3. BLYP-D3-DCP predicts BDEs for these bonds with an MAE of 2.0 kcal/mol. For all X–H and X–Y bonds, BLYP-D3-DCP outperforms B3LYP-D3 by ca. 30%.

For pericyclic (BHPERI) and Diels–Alder (DARC) reaction barrier heights, the results are mixed. In the case of the former database, BLYP-D3-DCP is outperformed by a factor of 2 by B3LYP-D3 (3.0 vs 1.5 kcal/mol MAE). Incidentally, the BLYP-D3-DCP/6-31+G(2d,2p) MAE associated with the BHPERI database is the same as that predicted by B3LYP-D3/def2-QZVP,²⁰ indicating that basis set incompleteness is playing a strong role in the predicted barrier heights. Basis set incompleteness also greatly affects the performance of B3LYP-D3/6-31+G(2d,2p) for the DARC set, for which a very large MAE of more than 31 kcal/mol is produced. This can be compared to an MAE of 16.4 kcal/mol for B3LYP-D3/def2-QZVP.²⁰ On the contrary, BLYP-D3-DCP performs well in comparison, giving an MAE of 6.7 kcal/mol for this database.

The performance of BLYP-D3-DCP/6-31+G(2d,2p) on the bond separation reactions as represented by the BSR36 database is somewhat inferior to B3LYP-D3/6-31+G(2d,2p), viz., 3.3 vs 2.5 kcal/mol, respectively, but outperforms B3LYP-D3/def2-QZVP (MAE = 5.9 kcal/mol).²⁰ The performance of BLYP-D3-DCP/6-31+G(2d,2p) on the RSE43 is inferior to B3LYP-D3 whether 6-31+G(2d,2p) or def2-QZVP basis sets are used in conjunction with the latter functional.

To summarize, with the 6-31+G(2d,2p) basis sets, BLYP-D3-DCP generally outperforms B3LYP-D3 in the prediction of binding energies of noncovalently bonded complexes and in the prediction of bond dissociation enthalpies for simple organic systems. With respect to the prediction of barrier heights for pericyclic and Diels–Alder reactions, BLYP-D3-DCP displays more uniform performance than does B3LYP-D3 but does not always outperform it: B3LYP-D3 displays better performance than BLYP-D3-DCP for the BSR36 and RSE43 databases. Collectively, these results suggest that BLYP-D3-DCP has some promise to perform at a level that is superior to an unadorned GGA functional. We remind the reader that entries in the GMTKN30 subdatabase that are listed in Table 7 were not part of the fitting set for the DCPs presented herein. It is likely that inclusion of barrier heights and other data into the DCP fitting would improve their performance more generally; however, the outcome of such an effort depends strongly on the underlying performance of the density-functional method. It is clear from the data presented herein that corrections to DFT-based methods, whether they be D3 or DCP corrections, tend to act in the same direction. For example, the D3 corrections will always increase BEs and BDEs and reduce barrier heights for reasons described above. Therefore, we suggest that the D3 and DCP corrections may be most effective if combined with a DFT method that behaves in a consistent manner with respect to all binding properties of interest (e.g., consistently underbinding). At this time we are not aware of a DFT-based method that display consistent behavior in this connection.

To close, we thought it would be interesting to consider the ability of BLYP-D3-DCP/6-31+G(2d,2p) to improve the

predictions of vibration frequencies relative to B3LYP-D3/6-31+G(2d,2p), in analogy to the work done by von Lilienfeld with FCACPs.³³ Figure 3 shows, and Table S13 in the Supporting Information details, the improvement in predicted zero-point energies (ZPE) in a series of small molecules using BLYP-D3-DCP over BLYP-D3. Without exception, the BLYP-D3-DCP ZPEs are in better agreement with B3LYP than are those obtained with BLYP without DCPs. The same can be said for individual frequencies that contribute to the ZPEs and to other thermochemical properties. Given that B3LYP predicts thermochemical parameters derived from vibrations (e.g., vibration contributions to enthalpy and to entropy) that are generally in better agreement with experimental values than are those obtained from BLYP,⁶⁰ the closer match between BLYP-D3-DCP predicted frequencies and associated thermochemical parameters to those values obtained by B3LYP demonstrates an additional benefit of the BLYP-D3-DCP approach.⁶¹

■ ASSOCIATED CONTENT

■ Supporting Information

A sample input file illustrating the use of DCPs with the Gaussian²¹ suite of programs, figure of PESs, tables listing full data for the S66, BDE, and GMTKN30 benchmark sets, parameters and tables listing performance of DCPs optimized for 6-31+G(2d,2p), 6-31+G(d,p), and 6-31G(d) basis sets, a table listing frequency calculation results, geometry optimization of example molecules, and the full ref 21. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jpca.5b02809.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to thank Prof. Philip Christiansen (Clarkson University), Dr. Alberto Otero de la Roza (National Institute for Nanotechnology), and Prof. Todd Martinez (Stanford) for helpful discussions. GAD is grateful to Compute Canada/Westgrid for a generous allocation of computing resources and to the University of British Columbia and NSERC for financial support.

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