Experimental Evidence for Multiple Oxidation Pathways in the (salen)Mn-Catalyzed Epoxidation of Alkenes

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Abstract: The substrate electronic effects on the selectivity in the catalytic epoxidation of *para*-substituted *cis* stilbenes **2a–i** were investigated by using (*R*,*R*)-[*N*,*N*′-bis(3,5-di-*t*Bu-salicylidene)-1,2-cyclohexanediamine]manganese(III) chloride **1** in benzene as the catalyst with iodosobenzene as the terminal oxidant. A Hammett study of the selectivity results reveals a stronger electrophilic character than previously assumed in the (salen)Mn-catalyzed reaction. In general, the best correlations with the experimental values were obtained by using the Hammett σ^+ values, which gave $\rho = -1.37$ for the rate of *cis*-epoxide formation and $\rho = -0.43$ for the rate of the stepwise process leading to the corresponding *trans* product. The reaction involves two separate pathways as indicated also by the competitive breakdown of the intermediate on the path to *trans* epoxide for methoxy-substituted substrates. The asynchronicity in the concerted pathway leading to *cis* epoxide is apparent for 4-methoxy-4′-nitrostilbene, which yields *cis* epoxide with 75% *ee* entirely as a result of electronic effects.

Keywords: asymmetric catalysis · epoxidation · linear free energy relationships · manganese · reaction mechanisms

Introduction

The selective epoxidation of unfunctionalized alkenes has been a major challenge in organic synthesis for many years.[1, 2] The successful development of optically active (salen)Mn catalysts has provided a useful tool for this transformation.[2, 3] In particular, conjugated *cis*-1,2-disubstituted alkenes are epoxidized with high to excellent enantioselectivity. The high degree of asymmetric induction displayed by (salen)Mn-based catalysts has initiated extensive mechanistic studies of the reaction,[2–4] which, to a large extent, parallels earlier investigations of porphyrin-based systems.[5]

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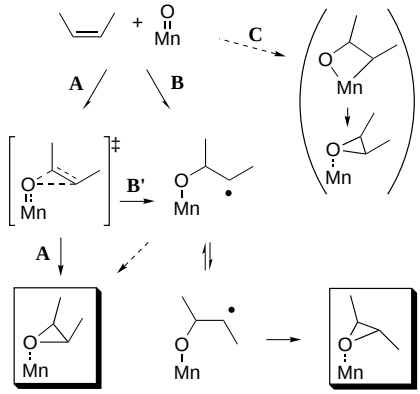
Isolated alkenes are believed to react in a concerted manner (Scheme 1, path **A**).[6] On the other hand, the formation of a mixture of *cis* and *trans* epoxides in the (salen)Mn-catalyzed epoxidation of conjugated *cis* alkenes,[7] as well as nonlinear behavior in Eyring-type plots of the enantioselectivity–temperature relationship,[8, 9] indicate a stepwise process. One proposal for a stepwise mechanism involves an irreversibly formed radical intermediate that collapses to *syn* and *anti* products (Scheme 1, path **B**).[3a] Another proposal involves a manganaoxetane that undergoes reductive elimination to the *syn* product or is opened to a radical intermediate that is transformed into the *anti* product



Scheme 1. Previously proposed reaction paths for (salen)Mn-catalyzed epoxidation.

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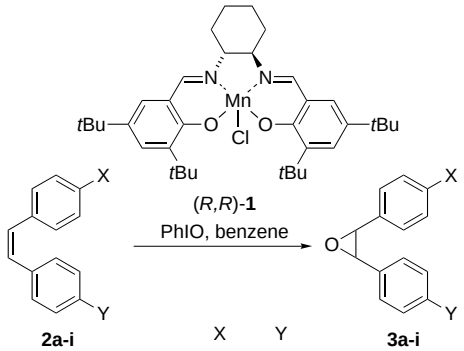
(Scheme 1, path **C**).[8, 10] However, experimental evidence has been presented that cannot be rationalized unambiguously by any of these mechanistic models. The results from a study of kinetic isotope effects are not consistent with the manganaoxetane pathway,[3a] but strong indications that *syn*-product formation does *not* proceed via a radical intermediate were found in another study by using cyclopropyl-substituted conjugated alkenes as radical traps.[11] An alternate model is needed to solve the conflict between the experimental results and these mechanistic proposals. Based upon a computational study, we presented instead a model, in which the timing of spin change along the reaction coordinate determines the choice of reaction path and, thus, the *syn*–*anti*-product distribution in the reaction.[12] This model provides a rationale for the contradictory experimental observations. It also accommodates the suggestion of Jacobsen and co-workers that the *cis* and *trans* epoxides are formed following a common selectivity-determining first step (Scheme 1, path **B′**),[3a] since the results from our study suggest that the spin change might occur either before or after the rate-limiting step.

Results and Discussion

We have undertaken an experimental study of the electronic effects in the title reaction as part of our ongoing effort to elucidate the mechanism of the reaction. We have chosen *para*-substituted *cis*-stilbenes as model substrates in our study. These are ideal substrates since the electronic properties at both carbons of the double bond can be modified by the *para*-substituents, while similar steric influence is maintained at both ends. Furthermore, the gross electronic properties of the two carbons are similar and allow the formation of a benzylic radical intermediate irrespective of the regioselectivity in the attack of the active oxidant. Separate Hammett expressions for the relative rates of *cis*- and *trans*-epoxide formation from these substrates can be obtained through competitive experiments. Conclusions can be drawn about the asynchronicity of the attack as well as the timing of the bifurcation to *syn* and *anti*-addition products along the reaction path, for example, if the common transition state postulate is feasible (Scheme 1, path **B′**). The substrate electronic effects on the title reaction have been investigated in previous Hammett studies. However, none of the studies include both competitive experiments with a reference substrate and determination of relative formation rates of *syn*- and *anti*-addition products individually.[7, 13] Our study proves this information to be critical for a detailed investigation of the mechanism of the reaction.

The reagents utilized in the study are shown in Scheme 2.[14] The substituents were chosen to cover a wide range of electronic properties and include symmetrically disubstituted compounds (**2a** and **2i**) as well as push–pull systems (**2f**). The observed rates of formation of epoxide relative to that of the unsubstituted product, **3c**, as well as yields and selectivities, are shown in Table 1. The relative overall rate constants for epoxide formation are within the same order of magnitude for all substrates, in agreement with previous reports by Kochi et al.[7] Qualitatively, the electronic influence on the reaction



	X	Y
a	NO_2	NO_2
b	NO_2	H
c	H	H
d	Br	H
e	Cl	H
f	NO_2	MeO
g	Br	MeO
h	H	MeO
i	MeO	MeO

Scheme 2. Reagents and products in the Hammett study.

Table 1. Epoxidation of *para*-substituted *cis*-stilbenes by using (*R*,*R*)-**1** and PhIO in benzene.[14]

	Substrate	k_{rel}[a, b]	yield[b, c]	*cis*:*trans*[b]	*ee cis*[d] [%]	*ee trans*[d] [%]
1	**2a**	0.4	nd[e]	4:96	[f]	85
2	**2b**	0.7	96	14:86	nd[e]	81
3	**2c**	1.0	99	25:75	[f]	75
4	**2d**	1.0	98	27:73	25	77
5	**2e**	1.1	98	29:71	23	76
6	**2f**	1.5	84	59:41	75	75
7	**2g**	1.7	85	58:42	61	68
8	**2h**	1.7	72	69:31	48	65
9	**2i**	2.9	64	86:14	[f]	26

[a] The relative rate constants for epoxidation were determined in competing experiments by using 0.2 equiv of PhIO with 0.5 equiv each of the substituted and unsubstituted *cis* stilbenes. [b] Determined by ^{1}H NMR spectroscopy and chiral HPLC on a Daicel Chiralcel OD column. [c] Determined after addition of 1 equiv of oxidant. [d] Determined by chiral HPLC on a Daicel Chiralcel OD column. [e] Not determined. [f] Not chiral.

rates fits into a general reaction mechanism, in which the alkene reacts with an electrophilic oxidation reagent.[15]

We have performed a systematic analysis of the results in Table 1 by using the Hammett equation for linear free energy relationships [Eq. (1)]. Several σ scales have been tested, but

$$\log(k_X/k_0) = \rho\sigma_X \quad (1)$$

all conclusions in this work are based on the σ^+ values since they consistently gave the best correlation with the experimental data.[16] The better fit could be obtained intuitively by considering the similarity in magnitude of the changes in the overall rates of epoxide formation k_{rel} for the symmetrically substituted substrates **2i** and **2a** versus **2c** (Table 1, entries 1, 3, and 9). These rate changes require the σ values to be similar in magnitude, but opposite in sign, for the methoxy and nitro substituents. This is the case for the σ^+ values (-0.78 and $+0.79$, respectively), but not for the other σ scales.[16]

We first made the simple assumption that the reaction rates of formation of the individual *cis*- and *trans*-epoxide isomers both vary with the average of the Hammett constants of the two substituents, that is, that the transition state is perfectly synchronous, and the two possible alkene face attacks are influenced equally by the two substituents [Eq. (2)].[16] The relative rates of formation of the isomeric epoxides $[(k_{XY}/k_0)_{cis}$ and $(k_{XY}/k_0)_{trans}]$ are plotted against the average σ^+ values in Figure 1.[17] The rates are presented also in Table 2 together with the σ^+ values employed.

$$\log(k_{XY}/k_0) = \rho(\sigma_X + \sigma_Y)/2 \quad (2)$$

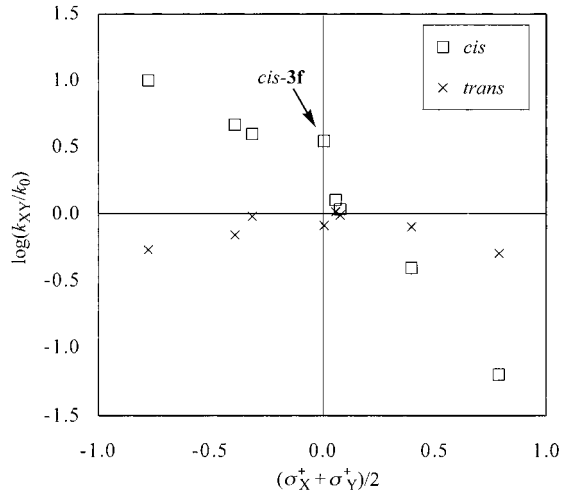


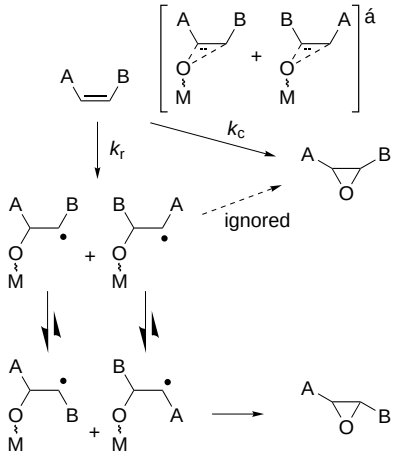
Figure 1. Hammett plot based on average σ^+ substituent constants [Eq. (2)].

Table 2. Hammett constants and relative rates of formation of single products.[17]

	Product	X	Y	σ^+_X	σ^+_Y	$(\sigma^+_X+\sigma^+_Y)/2$	$(k/k_0)_{cis}$	$(k/k_0)_{trans}$
1	**3a**	NO_2	NO_2	0.79	0.79	0.79	0.064	0.512
2	**3b**	NO_2	H	0.79	0	0.395	0.392	0.803
3	**3c**	H	H	0	0	0	1	1
4	**3d**	Br	H	0.15	0	0.075	1.080	0.973
5	**3e**	Cl	H	0.11	0	0.055	1.276	1.041
6	**3f**	NO_2	MeO	0.79	−0.78	0.005	3.540	0.820
7	**3g**	Br	MeO	0.15	−0.78	−0.315	3.944	0.952
8	**3h**	H	MeO	0	−0.78	−0.39	4.692	0.703
9	**3i**	MeO	MeO	−0.78	−0.78	−0.78	9.976	0.541

It is shown in Figure 1 that formation of the *cis* epoxides is strongly dependent on the substituents, whereas no clear effect can be seen on the formation of *trans* epoxide. We interpreted these observations as a first indication that *cis*- and *trans*-epoxide formation might occur following separate pathways. It is clear that the rate of *cis*-product formation is not influenced equally by the two substituents in *cis*-**3f** as it is formed 3.5 times faster than *cis*-**3c**, although the average σ^+ values for the two substrates are similar (Table 2, entries 3 and 6). Apparently, the formation of *cis*-**3f** follows a path that maximizes the effect of the activating methoxy substituent, and this gives a higher relative rate of formation than would be expected from the simplified expression in Equation (2).

To analyze the rate variations in more detail, we postulated a kinetic model involving a concerted and a stepwise pathway as shown in Scheme 3. We assumed that the first step of the radical process is irreversible and rate determining since no isomerized alkene was observed in the reaction after partial



Scheme 3. Postulated paths and constants employed in the kinetic model.

conversion. We also ignored the formation of *cis* product in the radical process since the equilibrium for C–C bond rotation is shifted far toward the intermediate leading to *trans* product (Table 1, entry 1). Our previous radical trapping study provided additional support for this assumption.[11] The complete suppression of *anti*-addition products from such traps strongly indicates that the ring closure of the intermediate radical to epoxide is substantially slower than trap opening. The high yields of nonisomerized epoxides in the same study show that the *syn* addition does *not* go through a radical intermediate. Thus, *cis* product is formed only by concerted addition (rate constant k_c), and the rate of *trans*-product formation is determined by the initial formation of the radical intermediate (rate constant k_r). Thereby, the rate ratio between the concerted and stepwise processes (k_c/k_r) is proportional to the *cis*–*trans*-epoxide product ratio since the two products are formed from the same alkene reactant. Note that no assumption was made at this point whether *syn* and *anti* products are formed via a common transition state (Scheme 1, path **B** or **B′**).

The simplified description of the electronic effects by using an effective Hammett constant expressed as the average of the two *para*-substituents [Eq. (2)] is valid only for a perfectly synchronous transition state. Perfect synchronicity is possible in a concerted process but unequal influence from the substituents would be expected in an asynchronous process, which could be either stepwise or concerted. Therefore, the regular Hammett expression was modified to describe a reaction with nonequal influence from the *para*-substituents of an unsymmetrical alkene. The possibility of two sterically identical but electronically dissimilar regiochemical attacks leads to the bis-exponential in Equation (3),[16] in which the

$$\log(k_{XY}/k_0) = \log[(10^{\rho[f\sigma_X+(1-f)\sigma_Y]} + 10^{\rho[f\sigma_Y+(1-f)\sigma_X]})/2] \quad (3)$$

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fraction f describes the relative influence of each substituent in each regiochemical attack. This value is to be determined in nonlinear fitting together with the reactivity coefficient ρ.

Equation (3) is solved easily for the two unknowns (ρ and f) by standard numerical methods for over-determined nonlinear equation systems.[18] The experimental $\log(k_{XY}/k_0)$ values for *cis*-epoxide formation were reproduced within experimental error ($r^2 = 0.98$, Table 3) by using the σ^+ values, whereas an attempted fit to other σ scales resulted in much worse correlation. The adjusted parameters indicate a substantial influence of the substituents on the rate of formation of *cis*-stilbene oxide ($\rho = -1.37$) and a stronger electrophilic character than has been assumed before in the (salen)Mn-catalyzed reaction.[19] It is clear that the formation of *cis* epoxide is an asynchronous process ($f = 0.87$), with the dominant influence coming from the more electron-donating substituent. Analysis of the push–pull system **2f** provides an additional confirmation about the asynchronicity of the reaction. The electronic effects of the two substituents in this substrate would be cancelled in a symmetric transition state (equal magnitude but opposite sign of the σ^+ values). However, the asynchronicity of the transition state allows the more activating substituent to dominate the reactivity in *cis*-epoxide formation, and thus it explains the high relative rate of *cis*-**3f** formation (Table 2, entry 6). Interestingly, high enantioselectivity is observed in the formation of this product even though the substituents are sterically similar (Table 1, entry 6), and the selectivity indicates that electronic effects play an important role in determining the alkene face selectivity in *syn* addition.

Table 3. The logarithmic values ($\log(k_{XY}/k_0)$), calculated based on σ^+ for the experimental and calculated relative rates of epoxide formation and radical intermediate formation.[a]

Product	*cis* exp	*cis* Eq. (3)	*cis* σ_{Eff}	*trans* exp	rad exp	rad Eq. (3)	rad σ_{Eff}
3a	−1.194	−1.082	0.790	−0.291	−0.297	−0.338	0.790
3b	−0.407	−0.376	0.274	−0.095	−0.081	−0.147	0.344
3c	0	0	0	0	0	0	0
3d	0.033	−0.096	0.070	−0.012	−0.006	−0.031	0.073
3e	0.106	−0.072	0.052	0.018	0.024	−0.023	0.054
3f	0.549	0.504	−0.368	−0.086	0.074	0.079	−0.186
3g	0.596	0.651	−0.476	−0.021	0.125	0.165	−0.385
3h	0.671	0.696	−0.508	−0.153	0.194	0.188	−0.439
3i	0.999	1.068	−0.780	−0.267	0.428	0.334	−0.780
ρ		−1.37		–[b]		−0.43	
f		0.87		–		0.91	
r^2		0.98		–		0.94	

[a] In this analysis, it is postulated that a radical intermediate is formed from the fraction of the alkene that is not converted to *cis* epoxide. This radical intermediate is only partly converted to *trans* epoxide; see text. [b] No positive correlation was obtained.

The analysis of the experimental rates of *trans*-epoxide formation is less tractable, and the rates could not be reproduced by using Equation (3).[16] It is evident from the data in Table 2, and also from Figure 1, that the rates of *trans*-epoxide formation show a nonlinear Hammett behavior, for which all substituents have a negative influence on the rates. This trend is opposite to what had been expected if substantial radical character were developed in the transition state as all substituents stabilize a radical better than hydrogen. Nonlinear behavior could also be indicative of a change in the rate-determining step. In our case, such a change would imply reversible formation of the intermediate radical (Scheme 3) and would result in *cis*–*trans* isomerization of the alkene. However, no stilbene isomerization was observed during the reactions. We recognized instead that the mass balance in Table 1 is incomplete for the methoxy-substituted stilbenes, and this implies that the rate of stilbene conversion is substantially faster than the rate of epoxide formation. The decrease in epoxide yields for electron-rich stilbenes was interpreted as an indication of a competing pathway leading to decomposition of the radical intermediate to non-epoxide products for these substrates.[20] To test this idea, we postulated that the rate of formation of the radical intermediate is equal to the rate of disappearance of stilbene, corrected for the rate of formation of *cis* epoxide, which was assumed to be formed following the concerted pathway (Scheme 3).[17] The resulting data are presented in Table 3. Now a fair fit was achieved between experimental and calculated rate constants, again using the σ^+ values. The ρ value is low, only -0.43, and the degree of asynchronicity is strong ($f = 0.91$).

The nonlinear enantioselectivity–temperature dependence observed by Katsuki et al.,[8] as well as the results from the study of radical traps,[11] are accommodated by the reaction mechanism in Scheme 3. In the study of Katsuki et al., the amounts of epoxides formed via a radical intermediate cannot be estimated since either C–C bond rotation is not permitted due to the cyclic structures (1,2-dihydronaphthalene and 1,3-cyclooctadiene), or the alkenes are monosubstituted (styrene and *p*-nitrostyrene). On the other hand, it is predicted from the reaction mechanism in Scheme 3 that nonlinear diastereoselectivity–temperature dependence and nonlinear enantioselectivity–temperature dependence for the *anti*-addition product would be expected in a system, in which the rates of the competing pathways are similar but with different temperature dependence.

The results obtained in this study are not easily depicted in a classical Hammett sense, since they depend on two interacting substituents for each stilbene. For illustration purposes, we have plotted in Figure 2 the experimental relative rates of *cis*- and *trans*-epoxide formation and the postulated rate of radical intermediate formation against an "effective Hammett substitution constant", σ_{Eff} [Eq. (4)]. The constant is calculated from Equation (3) as $\log(k_{XY}/k_0)_{calcd}/\rho$ for the two successful fits in Table 3 by using $f = 0.87$ for *cis* epoxide and $f = 0.91$ for *trans* epoxide and radical formation.

$$\log(k_{XY}/k_0) = \rho\sigma_{Eff} \{\sigma_{Eff} = \log(k_{XY}/k_0)_{calcd}/\rho \text{ [from Eq. (3)]}\} \quad (4)$$

The rate of concerted *syn* addition and the rate of the postulated radical intermediate formation both correlate well with the Hammett σ^+ values. The transition states for both processes are highly asynchronous where the buildup of charge on one carbon of the alkene in the rate-determining step is stabilized by through resonance from the closest *para*-substituent. The concerted pathway shows a large electronic

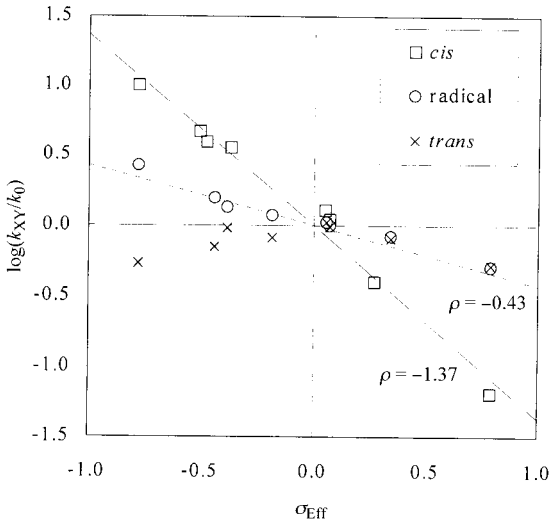

Figure 2. Experimental rates versus effective substituent constants [Eq. (4)].

dependence ($\rho = -1.37$) indicative of a late transition state. The transition state of the radical pathway is much earlier ($\rho = -0.43$) and has no significant radical character as indicated by the influence from the *para*-substituents. The stepwise *anti*-addition process displays a nonlinear behavior, interpreted as a competitive breakdown of the radical intermediate into non-epoxide products when electron-donating substituents are present on the stilbene.

Apparently *cis*- and *trans*-epoxide formation in the title reaction follow separate pathways. We cannot exclude the possibility of multiple oxidizing species in the reaction mixture, in which each species follows preferentially one of the reaction pathways.[21] These oxidants would show reaction rates, which have very different electronic dependence. In such a case the oxidants must be in rapid equilibrium under catalytic conditions, since the product distribution is affected significantly by the electronic properties of the substrate. The current results could be interpreted also as an attack on the alkene of a common electrophilic oxidizing species, but with subsequent branching to a radical intermediate *before* the transition state for the concerted *syn* addition, for example, by spin-surface crossing. In any case the common transition state hypothesis (Scheme 1, path **B′**) is excluded, and the fate of the alkene is sealed already in the first irreversible step.

Experimental Section

Experimental details and analytical data are available in the Supporting information. General procedure for epoxidation: (*R*,*R*)-**1** (12 mg, 0.02 mmol, 4 mol%), *para*-substituted stilbene **2** (0.5 mmol, 1 equiv), and iodosobenzene (110 mg, 0.5 mmol, 1 equiv) were stirred in benzene (4 mL) for 12 hours at room temperature. The catalyst residues were separated on a short silica column. The *cis*–*trans* ratio and enantiomeric purity were determined by ^{1}H NMR spectroscopy and chiral HPLC on a Daicel Chiralcel-OD column by using IPA/IB (isopropanol/hexanes). Competition experiments were performed starting with a 1:1 mixture of unsubstituted and substituted *cis*-stilbenes with oxidant (0.2 equiv).

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[1] K. A. Jørgensen, *Chem. Rev.* **1989**, *89*, 431–458.
[2] a) T. Katsuki, "*Asymmetric Epoxidation of Unfunctionalized Olefins and Related Reactions*" in *Catalytic Asymmetric Synthesis*, 2nd ed., (Ed.: I. Ojima), Wiley, New York, **2000**, pp. 287–326; b) E. N. Jacobsen, "*Asymmetric Catalytic Epoxidation of Unfunctionalized Olefins*" in *Catalytic Asymmetric Synthesis* (Ed.: I. Ojima), VCH, New York, **1993**, pp. 159–202.
[3] a) M. Palucki, N. S. Finney, P. J. Pospisil, M. L. Güler, T. Ishida, E. N. Jacobsen, *J. Am. Chem. Soc.* **1998**, *120*, 948–954; b) T. Katsuki, *J. Mol. Catal. A: Chem.* **1996**, *113*, 87–107; c) T. Katsuki, *Coord. Chem. Rev.* **1995**, *140*, 189–214.
[4] a) C. T. Dalton, K. M. Ryan, V. M. Wall, C. Bousquet, D. G. Gilheany, *Top. Catal.* **1998**, *5*, 75–91; b) T. Linker, *Angew. Chem.* **1997**, *109*, 2150–2152; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2060–2062.
[5] See, for example: a) M. Sono, M. P. Roach, E. D. Coulter, J. H. Dawson, *Chem. Rev.* **1996**, *96*, 2841–2887; b) D. Ostovic, T. C. Bruice, *Acc. Chem. Res.* **1992**, *25*, 314–320.
[6] H. Fu, G. L. Look, W. Zhang, E. N. Jacobsen, C.-H. Wong, *J. Org. Chem.* **1991**, *56*, 6497–6500.
[7] K. Srinivasan, P. Michaud, J. K. Kochi, *J. Am. Chem. Soc.* **1986**, *108*, 2309–2320.
[8] T. Hamada, T. Fukuda, H. Imanishi, T. Katsuki, *Tetrahedron* **1996**, *52*, 515–530.
[9] H. Buschmann, H.-D. Scharf, N. Hoffmann, P. Esser, *Angew. Chem.* **1991**, *103*, 480–518; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 477–515.
[10] P.-O. Norrby, C. Linde, B. Åkermark, *J. Am. Chem. Soc.* **1995**, *117*, 11035–11036.
[11] C. Linde, M. Arnold, P.-O. Norrby, B. Åkermark, *Angew. Chem.* **1997**, *109*, 1802–1803; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1723–1725.
[12] C. Linde, B. Åkermark, P.-O. Norrby, M. Svensson, *J. Am. Chem. Soc.* **1999**, *121*, 5083–5084.
[13] E. N. Jacobsen, L. Deng, Y. Furukawa, L. E. Martínez, *Tetrahedron* **1994**, *50*, 4323–4334.
[14] The *para*-substituted *cis*-stilbenes and (*R*,*R*)-**1** were prepared according to published procedures: a) H. Yamataka, K. Nagareda, K. Ando, T. Hanafusa, *J. Org. Chem.* **1992**, *57*, 2865–2869; b) W. Zhang, E. N. Jacobsen, *J. Org. Chem.* **1991**, *56*, 2296–2298; c) J. F. Larrow, E. N. Jacobsen, *J. Org. Chem.* **1994**, *59*, 1939–1942.
[15] K. G. Rasmussen, D. S. Thomsen, K. A. Jørgensen, *J. Chem. Soc. Perkin Trans. 1* **1995**, 2009–2017.
[16] Only the simplified kinetic expressions for the successful fits to the experimental data by using the σ^+ values are presented in this paper. The derivation of these expressions from the complete kinetic expressions are available in the Supporting information together with the various σ values used in the evaluation. Standard σ and σ^+ values for all substituents were obtained from a) M. B. Smith, J. March in *March's Advanced Organic Chemistry*, 5th ed., Wiley Interscience, New York, **2001**. Two different types of $\sigma^\bullet$ values were tested: the Creary scale: b) X. Creary, M. E. Mehrsheikh-Mohammadi, S. McDonald, *J. Org. Chem.* **1987**, *52*, 3254–3263; and the Jackson scale: c) H. Agirbas, R. A. Jackson, *J. Chem. Soc. Perkin Trans. 2* **1983**, *2*, 739–742; d) R. A. Jackson, *J. Organomet. Chem.* **1992**, *437*, 77–83.
[17] The relative rate constants were calculated from the experimental data in Table 1 by using the following expressions; $k_{cis} = k_c = k_{rel} \times (\%\ cis)/100$, $k_{trans} = k_{rel} \times (\%\ trans)/100$, $k_r = k_{rel} \times 100/(\%\ \text{yield}) - k_c$.
[18] The "solver" in Microsoft Excel98 for Macintosh was used to obtain the values of ρ and f giving the smallest sum of squares of deviations between experimental and calculated $\log(k_{rel})$.
[19] In a previous report by Jacobsen et al. (see: ref. [13]), correlation was found between the relative ratio of *cis*- and *trans*-epoxide formation

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[$\log(k_{cis}/k_{trans}) = \rho\sigma$] and the standard σ values. However, the individual rates of formation of the individual epoxide isomers could not be determined since no competitive experiments were performed against the unsubstituted substrate. We predict that such measurements would lead to conclusions similar to those presented here.

[20] The *cis*–*trans* ratio does not increase during the reaction. Therefore, the decrease in *trans*-epoxide formation cannot be explained by further oxidation of the *trans* epoxide to secondary products. Instead, use of excess oxidant leads to preferential loss of *cis* epoxide.

[21] Current suggestions of the nature of these oxidants involve oxomanganese(v) complexes in different spin states (see: ref. [12]; T. Strassner, K. N. Houk, *Org. Lett.* **1999**, *1*, 419–421; L. Cavallo, H. Jacobsen, *Angew. Chem.* **2000**, *112*, 602–604; *Angew. Chem. Int. Ed.* **2000**, *39*, 589–592; H. Jacobsen, L. Cavallo, *Chem. Eur. J.* **2001**, *7*, 800–807; J. El-Bahraoui, O. Wiest, D. Feichtinger, D. A. Plattner, *Angew. Chem.* **2001**, *113*, 2131–2134; *Angew. Chem. Int. Ed.* **2001**, *40*, 2073–2076; Y. G. Abashkin, J. R. Collins, S. K. Burt, *Inorg. Chem.* **2001**, *40*, 4040–4048); or Lewis acid activation of the stoichiometric oxidant by coordination to a manganese(III) complex in competition with an oxomanganese(v) complex (W. Adam, personal communication. See also: J. P. Collman, A. S. Chien, T. A. Eberspacher, J. I. Brauman, *J. Am. Chem. Soc.* **2000**, *122*, 11098–11100; W. Adam, C. Mock-Knoblauch, C. R. Saha-Möller, M. Herderich, *J. Am. Chem. Soc.* **2000**, *122*, 9685–9691; K. P. Bryliakov, D. E. Babushkin, E. P. Talsi, *J. Mol. Catal. A: Chem.* **2000**, *158*, 19–35; W. Adam, K. J. Roschmann, C. R. Saha-Möller, *Eur. J. Org. Chem.* **2000**, 3519–3521; D. Feichtinger, D. A. Plattner, *Chem. Eur. J.* **2001**, *7*, 591–599).

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