Novel chemoselective and diastereoselective iron(III)-catalysed Michael reactions of 1,3-dicarbonyl compounds and enones

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Iron(III) chloride hexahydrate catalyses the Michael reaction of 1,3-dicarbonyl compounds with α,β-unsaturated ketones under mild and neutral conditions with extraordinary efficiency. The chemoselectivity of this Fe^{III}-catalysed process is superior to that of the classic base-catalysed Michael reaction, since the latter suffers from various side reactions, namely drawbacks such as aldol cyclisations and ester solvolysis. Excellent yields and chemoselectivities together with the environmentally friendly nature of Fe^{III} catalysis makes this an important alternative to classic base catalysis. Moreover, the reaction procedure is reasonably easy: Fe^{III} catalysis does not require inert or anhydrous conditions, and in most cases no solvent is needed. In terms of diastereoselectivity, the Fe^{III}-mediated reaction may also prove superior to a base-catalysed one. In at least one example, Fe^{III} catalysis forms a diastereoisomer as the major kinetic product, which is disfavoured in the base-mediated Michael reaction, where a thermodynamic mixture is obtained. The relative configuration of the diastereoisomeric Michael products has been determined for two examples by synthesis and structure elucidation of the cyclic aldol derivatives.

Introduction

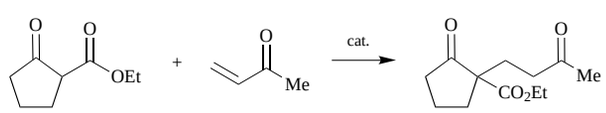
The Michael reaction of the 1,3-dicarbonyl compounds **1** and the enones **2** is classically a high yielding base-mediated process,[1] and can even be performed with high stereoselectivity.[2] However, there are some disadvantages with base catalysis, including side reactions of the starting materials and subsequent reactions of the Michael product **3**. Incompatibilities with base-sensitive groups, ester solvolysis and aldol processes leading to cyclic products or retro-aldol type decompositions can significantly decrease yields of the base-mediated Michael reactions in some cases. Alternatively, it has been reported that the Michael reaction can be catalysed by lanthanide[3] or transition metal[4] compounds, *e.g.* group VIII 1,3-dionato complexes,[5] although not always with satisfactory efficiency.

Recently, we reported that iron(III) chloride hexahydrate is an extraordinarily efficient catalyst for the Michael reaction of 1,3-dicarbonyl compounds and enones,[6] a hitherto unknown fact,‡ despite the known tendency of Fe^{III} to form 1,3-dionato complexes.[8] This ability, together with ecological and economical considerations make iron the transition metal of choice in such work. Fe^{III} catalyses the Michael reaction under mild and neutral conditions, and thus the chemoselectivity of the Fe^{III} catalysis is superior to that of the classic base-mediated process, since both side-reactions and subsequent reactions under basic conditions are avoided. Moreover, the reaction conditions for Fe^{III} catalysis are reasonably easy: no inert or anhydrous conditions are required and, in some cases, even solvents are unnecessary. This high efficiency together with excellent yields make the Fe^{III} catalysis of the Michael reaction an important alternative to the classic base catalysis.

Results and discussion

Iron(III) catalysis of the Michael reaction

We have been investigating the catalytic activity of several transition metal compounds in the Michael reaction of **1a** with **2a** to give **3a**[9] (Scheme 1). Although a number of the investigated



1a **2a** **3a**

Scheme 1

systems showed activity, only with $FeCl_3 \cdot 6\ H_2O$ was there fast, clean and complete conversion at room temperature. With 5 mol% the reaction was quantitative within 1 h, and with 1 mol% within 3 h. Results obtained with another Fe^{III} catalyst[4c] and some Ni^{II} compounds are listed in Table 1. Using $Fe(acac)_3$, which is not active itself but needed further Lewis acid activation, rapid consumption of starting materials was observed, too, but the conversion was not clean: **4a** (Table 2) was formed as a by-product *via* a hetero-Diels–Alder dimerisation of **2a**.[10] Of the Ni^{II} compounds only $Ni(acac)_2$[5] gave full conversion, but a high temperature was required. All other transition-metal compounds investigated in our studies are less efficient than the Ni^{II} compounds reported in Table 1.

Fe^{III} catalysis is generally very efficient in the conversion of various Michael donors **1** (see Table 2) with methyl vinyl ketone **2a**; a list of products **3** prepared is shown in Table 3. Best results were obtained with the cyclic keto esters to give **3a**, **3b**,[6] **3d**[11] and **3e**.[6] With only 1 mol% $FeCl_3 \cdot 6\ H_2O$ full conversion is achieved within a few hours at room temperature, even if bulkier ester functions are present (**3b**). Generally, no ester solvolysis side-reactions occur with ethyl or higher alkyl esters. Methyl esters like **1e** are partially solvolysed by the hydrate water of the catalyst,§ so that the product yield drops to 72%, if 5 mol% $FeCl_3 \cdot 6\ H_2O$ is used; with only 1 mol% of catalyst this side reaction is negligible (91% isolated yield).

Reactions of acyclic keto esters to give **3f**,[12] **3g**[13] and **3j**[14] as well as of β-diketones to give **3c**,[15] **3h**,[16] **3i**[17] and **3k**[18] proceed a

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‡ In one case the application of a combination of $Ni(acac)_2$ and $FeCl_3$ was reported, but the role of Fe^{III} was ascribed to its Lewis acid character (activation of the enone).[7]

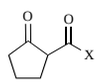
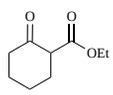
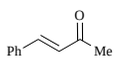
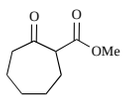
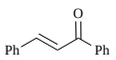
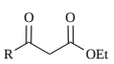
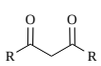
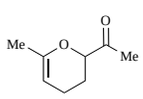
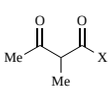
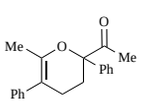
§ Decomposition product cycloheptanone was identified in the reaction mixture by GCMS.

Table 1 Comparison of Ni^{II} and Fe^{III} catalysis of the Michael reaction

Catalyst[a]	Conversion (%)[b]			
	1 h, RT[c]	3 h, RT	24 h, RT	3 h, 50 °C
$FeCl_3 \cdot 6\,H_2O$	100	—	—	—
$Fe(acac)_3 + BF_3 \cdot OEt_2$	40	90[d]	—	—
$NiCl_2 \cdot 6\,H_2O$	—	5	41	81
$Ni(OAc)_2 \cdot 4\,H_2O$	—	21	68	52
$Ni(acac)_2$	—	19	61	100

[a] Conditions: **1a** (1 equiv.) + **2a** (1.1 equiv.) + catalyst. (0.05 equiv.), no solvent. [b] By ^1H NMR. [c] Room temp. [d] By-product **4a** was formed.

Table 2 List of starting materials **1** and **2** and by-products **4**

	X = OEt X = OBu^i X = Me	**1a** **1b** **1c**		**2a**
		**1d**		**2b**
		**1e**		**2c**
	R = Me R = Ph	**1f** **1g**		**2d**
	R = Me R = Ph	**1h** **1i**		**4a**
	X = OEt X = Me	**1j** **1k**		**4b**

little slower, but use of 5 mol% of catalyst results in full conversion within a few hours at room temperature and gives satisfactory product yields. It should be emphasised that since the starting materials and products in Table 3 are liquid at room temperature no solvent is necessary for the transformations (except for **3i** which is solid at room temperature). Moreover, as long as reactions are quantitative with no by-products formation, the work-up procedure is reasonably simple: filtration using a small column of silica gel removes all iron-containing materials. In addition, since water is tolerated, no inert or anhydrous conditions are required, and reactions are carried out simply by mixing starting materials and the catalyst.¶

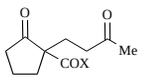
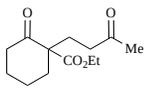
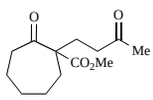
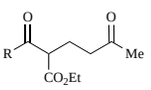
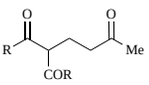
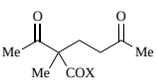
Fast and quantitative conversions together with a straightforward work-up procedure makes the iron(III) chloride hexahydrate-catalysed Michael reaction a very efficient alternative to the classic base-mediated methodology.

Chemoselectivity

In Table 4, products **3l**–**s** resulting from Michael reactions of various keto esters **1** (Table 2) with substituted enones **2b**–**d** (Table 2) are listed. Generally, these transformations need solvent, because the products are either solid or viscous oils at room temperature, and higher reaction temperatures (up to

¶ Scaling up (more than 20 mmol) requires cooling of the mixture to prevent **2a** from being evolved, since the reactions are slightly exothermic.

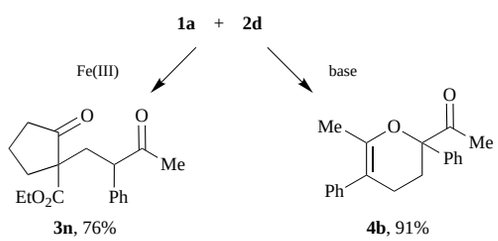
Table 3 Michael reactions of **1** with **2a** to give **3a**–**k**

Product			Fe^{III} (mol%)[a]	Yield (%)[b]
	X = OEt X = OBu^i X = Me	**3a** **3b** **3c**	1 1 5	97 95 86
		**3d**	1	94
		**3e**	1	91[c]
	R = Me R = Ph	**3f** **3g**	5 5	90 87
	R = Me R = Ph	**3h** **3i**	5 5	77 100[d]
	X = OEt X = Me	**3j** **3k**	5 5	78 84

[a] Conditions **1** (1 equiv.) + **2a** (1.1 equiv.) + catalyst $FeCl_3 \cdot 6\,H_2O$, no solvent, room temp. [b] Isolated yields. [c] Use of 5 mol% catalyst resulted in 72% yield. [d] Solvent ($CHCl_3$) was applied.

50 °C) are required in some cases (see Experimental section for details).

The iron(III)-catalysed conversion of the keto ester **1a** with the enone **2d** to the Michael product **3n** provides a typical example of the chemoselectivity achieved with this method (Scheme 2). Base catalysis, namely 5 mol% KOEt in absolute

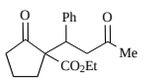
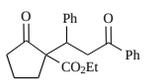
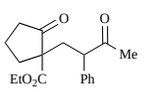
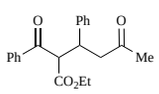
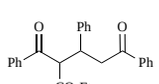
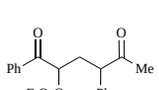
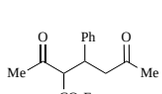
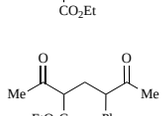


Scheme 2

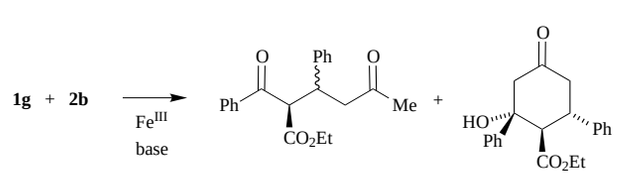
EtOH, failed to give any of the desired product **3n**, the enone dimer **4b**[19] being obtained instead from a hetero Diels–Alder reaction of two equivalents of **2d**. A similar result was obtained in the base-mediated conversion of Michael donors **1f** and **1g** with the enone **2d**. In these cases no Michael products **3q**[20] or **3s**[20] were detected in the reaction mixtures, only the dimer **4b** being isolated. Thus, the Fe^{III}-catalysed reaction of the keto esters **1** with the enone **2d** seems to be the only way to perform a Michael reaction, and indeed products **3n**, **3q** and **3s** were isolated in good to moderate yields, although the dimer **4b** was also found in these reactions as a by-product (see Experimental section). Obviously, with Fe^{III} catalysis the Michael reaction of **2d** becomes fast enough to compete seriously with the Diels–Alder dimerisation side-reaction.

The Michael adduct **3o**[20] was formed by Fe^{III}-catalysed conversion of **1g** with the acceptor **2b** in good yield (Scheme 3). In contrast, under conditions of base catalysis the primary product **3o** cyclises in a subsequent aldol reaction to give **5a**,[21] a by-product which is not detectable in an Fe^{III} catalysed reaction. Thus, the optimum yield achievable in the base-mediated

Table 4 Fe^{III} and base-catalysed Michael reactions of **1** with **2b–d** to give **3l–s** compared

Product		Fe^{III} [a]		Base [b]	
		yield (%)	A/B [c]	yield (%)	A/B [c]
	**3l**	90	20:80	93	31:69
	**3m**	93	49:51	100	46:54
	**3n**	76 [d]	82:18	0 [e]	—
	**3o**	84	16:84	48 [f]	61:39
	**3p**	85	78:22	100	90:10
	**3q**	74 [d]	57:43 [g]	0 [e]	—
	**3r**	76	57:43 [g]	0 [h]	—
	**3s**	46 [d]	55:45 [g]	0 [e]	—

[a] Conditions: **1** (1.0 equiv.) + **2** (1.0 equiv.) + $FeCl_3 \cdot 6\ H_2O$ (0.01–0.05 equiv.), solvent $CHCl_3$, stirring overnight. [b] Conditions: **1** (1.0 equiv.) + **2** (1.0 equiv.) + KOH (0.05 equiv.), solvent abs. EtOH, stirring overnight. [c] In all cases the diastereoisomer with the ester-CH_3 triplet in the ^1H NMR spectrum at higher field was assigned as isomer A, the one with the triplet at lower field is isomer B. [d] By-product **4b** was formed. [e] Product **4b** only. [f] By-product **5a** was formed. [g] Isomers in equilibrium with each other. [h] Isomeric mixtures of cyclic aldol products were obtained.



Scheme 3

process is 48% and much lower than in a Fe^{III}-catalysed reaction: in fact, if the base-catalysed reaction were to run for infinite time, the yield of **3o** would drop to zero, all the material by then having been consumed by the aldol process. A more extreme example is compound **3r** [22] which, whilst readily accessible by Fe^{III} catalysis, was not formed at all by base catalysis, since subsequent aldol reactions led to isomeric mixtures of unseparated and uncharacterised cyclic products.

In summary, we have outlined how Fe^{III} catalysis of the Michael reaction can provide access to compounds, which cannot be prepared by classic base catalysis as a result of side-reactions or subsequent reactions taking place with the latter. Consequently, Fe^{III} has to be considered as an alternative in the synthesis of novel Michael reaction products, particularly, if base catalysis fails to give satisfactory results or fails altogether. There are examples, of course, in which Fe^{III} and base-mediated Michael reactions are both efficient, *e.g.* to prepare **3l**,[23] **3m** or **3p**.[24]

Diastereoselectivity

If Michael donors **1** are allowed to react with the enones **2b–d**, which bear a substituted carbon–carbon double bond, each product consists of two diastereoisomers **A** and **B**. In all the examples listed in Table 4 formation of these two diastereoisomers is observed, and their ratio **A/B**‖ has been determined for Fe^{III} as well as for base catalysis (the latter provided that a Michael product was formed at all). For the products in Table 4 the diastereoisomers were separated by chromatography and each completely characterised, except for **3q**, **3r** and **3s**. In these cases products contain a β-keto ester moiety, and the two diastereoisomers were in equilibrium *via* the corresponding enol form, which was actually detectable in the ^1H NMR spectra of **3q**, **3r** and **3s** (*ca.* 0.5 mol%; integral of the OH resonance at *ca.* δ 13 ppm). Thus, isomers were not separable. In contrast, isomers of **3l**, **3m** and **3n** were separable because of a quaternary carbon centre; however with regard to diastereoselectivity, the results of Fe^{III} and base catalysis were not significantly different.

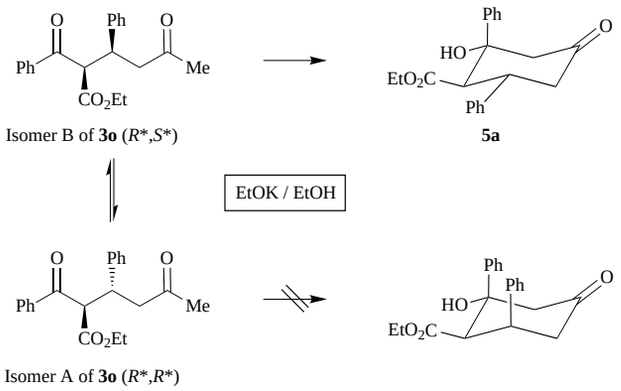
Interestingly, compounds **3o** and **3p**, which also bear a β-keto ester moiety with a formal acidified C–H bond, failed to equilibrate and in both cases the two diastereoisomers obtained with Fe^{III} catalysis could be separated by chromatography. They failed to interconvert both under neutral conditions, even at temperatures up to 150 °C, and also under the reaction conditions of the Fe^{III} catalysis. Nevertheless, an equilibrium mixture of **3o** was obtained with 1 equiv. of NEt_3 in $CDCl_3$ within 2 h, and with 5 equiv. of CF_3CO_2H in $CDCl_3$ within 10 d. In both cases the thermodynamic equilibrium was found to be **A/B** = 60/40, a similar result to that obtained with the base-catalysed formation of **3o** (**A/B** = 61/39). Fe^{III} catalysis led to a kinetic mixture with **A/B** = 16/84; contrastingly, Fe^{III} and base-mediated formation of **3p** gave roughly the same product ratio. In summary, Fe^{III} catalysis of the Michael reaction introduces the opportunity to obtain kinetic product mixtures in cases in which base catalysis yields thermodynamic ratios. As shown for **3o**, these kinetic and thermodynamic mixtures can differ significantly.

The inability of the isomers of **3o** and **3p** to interconvert seems to be closely linked to the 1,3-diphenyl constitution of the products: thus, if the phenyl groups are in a 1,4 relationship to each other '**3q**' or one is missing '**3r**', the corresponding species are in equilibrium again. Presumably, the enol form, which is the intermediate species in an equilibrium of the two diastereoisomers, cannot be stabilised by H-bonding because of allylic 1,3-strain,[25] and thus is not formed.

Relative configuration

The formation of **5a** in the base-catalysed conversion of **1g** and **2b** (as a by-product at room temp. and main product at elevated temp.) allowed the assignment of the relative configuration of the diastereoisomers **A** and **B** of **3o**. In independent experiments starting from pure isomers of **3o** it was shown that base catalysis (either NEt_3 or KOH in absolute EtOH) converts isomer **B** directly into the cyclic product **5a**, whilst isomer **A** reacted relatively slower and—after equilibration with **B**—gives **5a** as well (Scheme 4). Consequently, the relative configuration of the stereocentres in isomer **B** should be the same as in **5a**, in

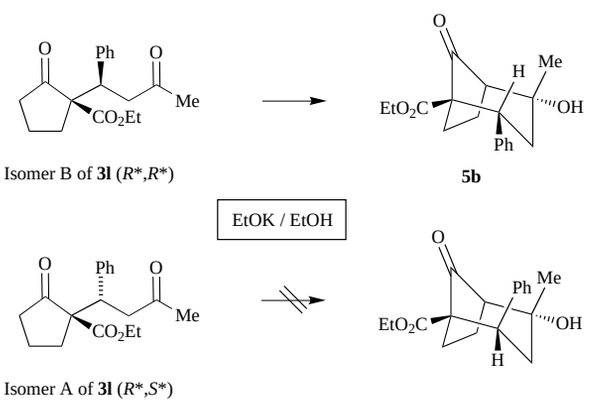
‖ In all cases the diastereoisomer with the ester-CH_3 triplet in the ^1H NMR spectrum at higher field is assigned to be isomer **A**, the one with the triplet at lower field is isomer **B**.



Scheme 4

which the ethoxycarbonyl and the phenyl group have been reported to be both equatorial and *trans* to each other; in fact the $^3J_{16}$ H,H-coupling constant in **5a** was found to be 2.8 Hz. Thus, isomer **B** of **3o**, the major product with Fe^{III}, is the (*R**,*S**)-isomer, and isomer **A**, which is the thermodynamic product, is assigned to be (*R**,*R**). Analogously, the same relative configuration applies for the two isomers of **3p**, since their ^{1}H NMR spectra show ABMX patterns, which are nearly identical with those of **3o**.

In the same manner, isomer **B** of **3l** cyclises under basic reaction conditions to give the bicyclic derivative **5b** (Scheme 5), the assignment of structure to which was made on the basis of H,H-COSY and NOE experiments. In a similar way to **5a**, the ethoxycarbonyl and phenyl groups are both equatorial (for the chair-conformation of the six-membered ring as shown in Scheme 5) and *trans* to each other. Also, the phenyl and methyl



Scheme 5

groups are *trans*, and the hydroxy function is in an equatorial position. Isomer **A** of **3l** failed to give any aldol product under either the same or even more drastic reaction conditions. A cyclisation product analogous to **5b** would bear the phenyl group in an axial position and *cis* to either an hydroxy or a methyl group, a situation which is impossible because of 1,3-strain. Consequently, the relative configuration of isomer **B** is (*R**,*R**), and that of isomer **A** must be (*R**,*S**). By comparison of the ^{1}H NMR data, relative configurations of **3m** can be assigned analogously.

Conclusion

Iron(III) catalysis is proposed as a highly efficient alternative to base catalysis of the Michael reaction for 1,3-dicarbonyl compounds and enones. Conversion is generally fast and clean, performance and work-up easy and in some cases solvents are unneeded; further, $FeCl_3 \cdot 6\ H_2O$ is both an ecologically friendly compound and relatively cheap. In terms of chemoselectivity, iron(III) catalysis can yield Michael reaction products even in cases where base catalysis gives poor results or fails altogether. As to diastereoselectivity, iron(III) catalysis can produce kinetic mixtures of diastereoisomers even in cases where base catalysis leads to a thermodynamic equilibrium mixture.

Experimental

Column chromatography was accomplished with Merck silica gel (Type 60, 0.063–0.200 mm) using methyl *tert*-butyl ether (MTB). ^{1}H NMR: Bruker AM 400 (400 MHz), 25 °C, TMS; structure elucidation was made using H,H-COSY and NOE experiments. ^{13}C NMR: Bruker AC 200 (50 MHz), 25 °C, TMS, assignments were made using DEPT experiments. *J* values given in Hz. MS: Varian MAT 711 and MAT 955Q (high resolution). IR: Nicolet Magna IR 750. GC and GCMS: HP 5890 II with FID resp. HP MSD 5971A. Elemental analyses: Analytik Jena Vario EL. All starting materials were either commercially available or were prepared according to literature procedures (**1b**,[26] **1j**,[27] **1k**,[28] **2d**[29]).

Ethyl 2-oxo-1-(3-oxobutyl)cyclopentanecarboxylate 3a

A mixture of the oxo ester **1a** (875 mg, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (15 mg, 0.055 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.41) to afford **3a** as a colourless oil (1.23 g, 5.44 mmol, 97%); ν_{max}/cm^{-1} (ATR) 2976m, 1748vs, 1717vs, 1448m, 1406m, 1367m, 1318m, 1260s, 1232s, 1165s, 1116m, 1029m and 861m; δ_H(400 MHz, $CDCl_3$): 1.23 (t, *J* 7.2, 3 H, CH_3), 1.82–2.03 (m, 4 H, CH_2), 2.03–2.13 (m, 1 H, CH*H*), 2.12 (s, 3 H, CH_3), 2.24–2.49 (m, 4 H, CH_2), 2.69 (ddd, *J* 18, 9.6, 6.0, 1 H, C*H*H) and 4.14 (q, *J* 7.1, 2 H, OCH_2) ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$) δ 13.29 (CH_3), 18.84 (CH_2), 26.24 (CH_2), 29.00 (CH_3), 33.22 (CH_2), 37.07 (CH_2), 38.01 (CH_2), 58.23 (C), 60.23 (OCH_2), 170.47 (C=O), 206.61 (C=O) and 213.75 (C=O); *m*/*z* (EI, 70 eV), 226 (11%) [M^+], 208 (10) [$M^+ - H_2O$], 198 (86) [$M^+ - CO$], 169 (17) [$M^+ - Me(CO)CH_2$], 156 (49) [$M^+ - Me(CO)CH{=}CH_2$], 152 (19) [$M^+ - EtOCHO$], 141 (18) [$M^+ - Me(CO)CH{=}CH_2 - Me$], 137 (50) [$M^+ - EtOCHO - Me$], 125 (100) [$M^+ - EtOCHO - CH_2{=}CH$], 110 (54) [$M^+ - EtOCO - MeCO$], 55 (29) [$CH_2COMe^+$] and 43 (86) [$COMe^+$] [Found: C, 63.68; H, 8.09%; M (HRMS), 226.1207. Calc. for $C_{12}H_{18}O_4$: C, 63.70; H, 8.02%, *M*, 226.1205].

Isobutyl 2-oxo-1-(3-oxobutyl)cyclopentanecarboxylate 3b

A mixture of the oxo ester **1b** (1.03 g, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (15 mg, 0.055 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.45) to afford **3b** as a colourless oil (1.35 g, 5.32 mmol, 95%); ν_{max}/cm^{-1} (ATR) 2964s, 2892m, 2876m, 1749vs, 1718vs, 1471m, 1370s, 1356m, 1259s, 1230s, 1165s, 1117m and 998m; δ_H(400 MHz, $CDCl_3$) 0.91 (d, *J* 6.6, 6 H, 2 CH_3), 1.84–2.15 (m, 6 H, CH, CH_2), 2.13 (s, 3 H, CH_3), 2.25–2.52 (m, 4 H, CH_2), 2.70 (ddd, *J* 18, 9.1, 6.2, 1 H, CH*H*) and 3.84–3.92 (m, 2 H, OCH_2); ^{13}C{^{1}H} NMR (50 MHz, $CDCl_3$) δ 18.72 (2 CH_3), 19.37 (CH_2), 26.79 (CH_2), 27.47 (CH), 29.62 (CH_3), 34.08 (CH_2), 37.72 (CH_2), 38.62 (CH_2), 58.73 (C), 71.08 (OCH_2), 171.13 (C=O), 207.38 (C=O) and 214.42 (C=O); *m*/*z* (EI, 70 eV), 254 (1%) [M^+], 236 (5) [$M^+ - H_2O$], 226 (41) [$M^+ - CO$] and 125 (100) [$M^+ - Bu^i - CO - Me_2CO$] [Found: C, 66.46; H, 8.78%; M (HRMS), 254.1522. Calc. for $C_{14}H_{22}O_4$: C, 66.12; H, 8.72; *M*, 254.1518].

2-Acetyl-2-(3-oxobutyl)cyclopentanone 3c

A mixture of the diketone **1c** (706 mg, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (76 mg, 0.28 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.42) to afford **3c** as a colourless oil (946 mg, 4.82 mmol, 86%); ν_{max}/cm^{-1} 2966m, 2890w, 1735s, 1702vs, 1421m, 1407m, 1358s, 1317m, 1276m, 1248m, 1163s, 1147s, 1116m, 929m and 815m; δ_H(400 MHz, $CDCl_3$) 1.62–1.69 (m, 1 H), 1.85–1.97 (m, 4 H), 2.11 (s, 3 H,

CH_3), 2.16 (s, 3 H, CH_3), 2.28–2.38 (m, 4 H) and 2.05–2.57 (m, 1 H); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 19.09 (CH_2), 25.84 (CH_3), 27.30 (CH_2), 29.65 (CH_3), 31.21 (CH_2), 38.08 (CH_2), 38.31 (CH_2), 67.11 (C), 204.33 (C=O), 206.86 (C=O) and 215.72 (C=O); *m*/*z* (EI, 70 eV), 196 (1%) [M^+], 154 (100) [$M^+ - CH_2CO$], 97 (84) [$M^+ - CH_2CO - MeCOCH_2$] and 43 (94) [$MeCO^+$] [Found: C, 66.92; H, 8.24%; M (HRMS), 196.1103. Calc. for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22%; *M*, 196.1099].

Ethyl 2-oxo-1-(3-oxobutyl)cyclohexanecarboxylate 3d

A mixture of the oxo ester **1d** (953 mg, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol), and $FeCl_3 \cdot 6\ H_2O$ (15 mg, 0.055 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.46) to afford **3d** as a colourless oil (1.26 g, 5.26 mmol, 94%); ν_{max}/cm^{-1} (ATR) 2940s, 2867m, 1711vs, 1445s, 1367s, 1244s, 1212s, 1188s, 1168s, 1137m, 1096m and 1020m; δ_H(400 MHz, $CDCl_3$) 1.24 (t, *J* 7.2, 3 H, CH_3), 1.38–1.48 (m, 1 H, CH*H*), 1.56–1.65 (m, 2 H, CH_2), 1.68–1.76 (m, 1 H), 1.81 (ddd, *J* 14, 10, 5.4, 1 H, CH*H*), 1.92–2.01 (m, 1 H, C*H*H), 2.05 (ddd, *J* 14, 10, 5.0, 1 H, CH*H*), 2.09 (s, 3 H, CH_3), 2.33 (ddd, *J* 18, 10, 5.4, 1 H, CH*H*), 2.39–2.50 (m, 3 H, CH_2), 2.55 (ddd, *J* 18, 10, 5.2, 1 H, C*H*H) and 4.11–4.23 (m, 2 H, OCH_2); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.47 (CH_3), 21.90 (CH_2), 26.85 (CH_2), 27.72 (CH_2), 29.14 (CH_3), 35.86 (CH_2), 37.99 (CH_2), 40.30 (CH_2), 59.25 (C), 60.64 (OCH_2), 171.22 (C=O), 206.67 (C=O) and 206.87 (C=O); *m*/*z* (EI, 70 eV), 240 (3%) [M^+], 212 (17) [$M^+ - CO$], 194 (22) [$M^+ - CO - H_2O$], 170 (100) [$M^+ - CH_2CH(CO)Me$], 151 (54) [$M^+ - H_2O - CH_2CH_2(CO)Me$] and 124 (62) [$M^+ - H_2O - CO - CH_2CH(CO)Me$] [Found: C, 64.64; H, 8.37%; M (HRMS), 240.1362. Calc. for $C_{13}H_{20}O_4$: C 64.98, H 8.39%; *M*, 240.1362].

Methyl 2-oxo-1-(3-oxobutyl)cycloheptanecarboxylate 3e

A mixture of the oxo ester **1e** (929 mg, 5.46 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (15 mg, 0.055 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.45) to give **3e** as a colourless oil (1.20 g, 4.99 mmol, 91%); ν_{max}/cm^{-1} (ATR) 2935s, 2861m, 1734sh, 1714vs, 1444s, 1437s, 1356m, 1295m, 1257m, 1229s, 1198s, 1165s, 992s, 941s; δ_H(400 MHz, $CDCl_3$) 1.38–1.55 (m, 2 H, CH_2), 1.58–1.75 (m, 5 H, CH_2), 1.79–1.92 (m, 1 H, CH*H*), 1.88 (ddd, *J* 14, 10, *J* 5.6, 1 H, C*H*H), 2.10 (s, 3 H, CH_3), 2.15 (ddd, *J* 14, 10, 5.6, 1 H, CH*H*), 2.39 (ddd, *J* 18, 10, 5.6, 1 H, C*H*H), 2.45–2.65 (m, 3 H, CH_2) and 3.70 (s, 3 H, OCH_3); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 24.49 (CH_2), 24.99 (CH_2), 28.82 (CH_2), 29.34 (CH_2), 29.38 (CH_3), 33.48 (CH_2), 38.57 (CH_2), 41.68 (CH_2), 51.69 (OCH_3), 61.32 (C), 172.39 (C=O), 206.99 (C=O) and 208.87 (C=O); *m*/*z* (EI, 70 eV), 240 (3%) [M^+], 222 (4) [$M^+ - H_2O$], 212 (7) [$M^+ - CO$], 150 (70) [$M^+ - MeOCO - MeO$], 98 (57) [$COCH_2CH_2CH_2CH_2CH_2^+$], 95 (85) [$MeCOCH_2CH_2CH_2CH_2^+$] and 43 (100) [$MeCO^+$] [Found: C, 65.03; H, 8.39%; M (HRMS), 240.1367. Calc. for $C_{13}H_{20}O_4$: C, 64.98; H, 8.39%; *M*, 240.1362].

Ethyl 2-acetyl-5-oxohexanoate 3f

A mixture of the oxo ester **1f** (728 mg, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol), and $FeCl_3 \cdot 6\ H_2O$ (76 mg, 0.28 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.38) to afford **3f** as a colourless oil (1.01 g, 5.04 mmol, 90%); ν_{max}/cm^{-1} (ATR) 2983m, 2940m, 1738vs, 1713vs, 1445m, 1419m, 1359s, 1244s, 1217s, 1151s, 1097m, 1023m, 957m and 858m; δ_H(400 MHz, $CDCl_3$) 1.22 (t, *J* 7.2, 3 H, CH_3), 1.97–2.11 (m, 2 H, 3-CH_2), 2.09 (s, 3 H, CH_3), 2.19 (s, 3 H, CH_3), 2.43–2.48 (m, 2 H, 4-CH_2), 3.45 (t, *J* 7.2, 1 H, 2-CH) and 4.10–4.18 (m, 2 H, OCH_2); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 13.55 (CH_3), 21.20 (CH_2), 28.45 (CH_3), 29.32 (CH_3), 39.92 (CH_2), 57.70 (CH), 60.86 (OCH_2), 168.98 (C=O), 202.26 (C=O) and 206.88 (C=O); *m*/*z* (EI, 70 eV), 200 (0.5%) [M^+], 158 (24) [$M^+ - CH_2CO$], 112 (17) [$M^+ - EtOCO - Me$], 101 (23) [$M^+ - Et - MeCOCH_2CH_2$], 84 (35) [$M^+ - EtOH - MeCOCH_2CH_2$] and 43 (100) [$MeCO^+$] [Found: C, 59.85; H, 8.05%; M (HRMS), 200.1053. Calc. for $C_{10}H_{16}O_4$: C, 59.98; H, 8.05%; *M*, 200.1049].

Ethyl 2-benzoyl-5-oxohexanoate 3g

A mixture of the oxo ester **1g** (1.08 g, 5.60 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (76 mg, 0.28 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.46) to afford **3g** as a colourless oil (1.28 g, 4.87 mmol, 87%); ν_{max}/cm^{-1} (ATR) 3063w, 2982m, 2940m, 2905w, 1735vs, 1715vs, 1685vs, 1597m, 1448m, 1369m, 1286m, 1246s, 1180s, 1157s, 1025m and 691m; δ_H(400 MHz, $CDCl_3$) 1.16 (t, *J* 7.1, 3 H, CH_3), 2.13 (s, 3 H, 6-CH_3), 2.15–2.30 (m, 2 H, 3-CH_2), 2.52–2.67 (m, 2 H, 4-CH_2), 4.08–4.20 (m, 2 H, OCH_2), 4.44 (dd, *J* 6.3, 7.9, 1 H, 2-CH), 7.47–7.50 (m, 2 H, ArH), 7.57–7.61 (m, 1 H, ArH) and 8.01–8.03 (m, 2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.62 (CH_3), 22.42 (CH_2), 29.56 (CH_3), 40.13 (CH_2), 52.30 (CH), 61.00 (OCH_2), 128.32 (2 CH), 128.44 (2 CH), 133.30 (CH), 135.67 (C), 169.42 (C=O), 194.89 (C=O) and 207.36 (C=O); *m*/*z* (EI, 70 eV), 262 (0.1%) [M^+], 105 (100) [$PhCO^+$], 77 (56) [Ph^+] and 43 (86) [MeCO] [Found: C, 68.36; H, 6.90%; M (HRMS), 262.1149. Calc. for $C_{15}H_{18}O_4$: C, 68.69; H, 6.92%; *M*, 262.1205].

3-Acetylhepta-2,6-dione 3h

The enone **2a** (2.0 ml, 24.0 mmol) was added to a mixture of the diketone **1h** (2.40 g, 24.0 mmol) and $FeCl_3 \cdot 6\ H_2O$ (324 mg, 1.20 mmol) at 0 °C. The resulting mixture was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.34) to afford **3h** as a colourless oil (3.13 g, 18.4 mmol, 77%) (mixture of tautomers, NMR data are given for the major isomer). An analytically pure sample of **3h** was obtained by Kugelrohr distillation (60 °C at 0.5 mm); ν_{max}/cm^{-1} (ATR) 2970w, 2941w, 1699vs, 1569w, 1420m, 1358s and 1154s; δ_H(400 MHz, $CDCl_3$) 2.07 (q, *J* 7.0, 2 H, 4-CH_2), 2.12 (s, 3 H, 7-CH_3), 2.19 (s, 6 H, 1,1′-CH_3), 2.44 (t, *J* 7.0, 2 H, 5-CH_2) and 3.67 (t, *J* 7.0, 1 H, 3-CH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 20.98 (CH_2), 28.81 (2 CH_3), 29.32 (CH_3), 39.99 (CH_2), 66.13 (CH), 203.55 (2 C=O) and 206.79 (C=O); *m*/*z* (EI, 70 eV), 170 (1%) [M^+], 152 (9) [$M^+ - H_2O$], 137 (100) [$M^+ - H_2O - Me$], 109 (26) [$M^+ - H_2O - COMe$] [Found: C, 63.72; H, 8.11%; M (HRMS), 170.0942. Calc. for $C_9H_{14}O_3$: C, 63.51; H, 8.29%; *M*, 170.0943].

2-Benzoyl-1-phenylhexane-1,5-dione 3i

A solution of the dione **1i** (1.22 g, 5.46 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (74 mg, 0.274 mmol) in $CHCl_3$ (1.5 ml) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1:5; R_f 0.50) to afford **3i** as colourless crystals (1.60 g, 5.44 mmol, 100%), mp 60 °C (recryst. from MTB); ν_{max}/cm^{-1} (ATR) 3062m, 3003w, 2937m, 1711vs, 1694vs, 1670vs, 1596s, 1448s, 1430m, 1409m, 1368m, 1349s, 1324m, 1306m, 1285m, 1257s, 1233m, 1209m, 1199s, 1181s, 1160s, 1075w, 1064w, 1000m, 936m, 921m, 790m, 758m, 728m and 693vs; δ_H(400 MHz, $CDCl_3$) 2.13 (s, 3 H, 6-CH_3), 2.32 (q, *J* 6.5, 2 H, 3-CH_2), 2.71 (t, *J* 6.4, 2 H, 4-CH_2), 5.49 (t, *J* 6.7, 1 H, 2-CH), 7.44–7.48 (m, 4 H, ArH), 7.55–7.60 (m, 2 H, ArH) and 8.03–8.05 (m, 4 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 22.94 (3-CH_2), 29.73 (6-CH_3), 40.50 (4-CH_2), 54.46 (2-CH), 128.38 (4 CH), 128.68 (4 CH), 133.39 (2 CH), 135.57 (2 C), 196.04 (2 C=O) and 208.29 (C=O); *m*/*z* (EI, 70 eV), 294 (0.1%) [M^+], 276 (0.5) [$M^+ - H_2O$], 251 (1) [$M^+ - MeCO$], 236 (2) [$M^+ - Me_2CO$], 224 (4) [$M^+ - MeCOCH{=}CH_2$], 189 (10) [$M^+ - PhCO$], 172 (20) [$M^+ - PhCOOH$], 105 (100) [$PhCO^+$] and 77 (28) [Ph^+] [Found: C, 77.53; H, 6.29%; M (HRMS), 294.1243. Calc. for $C_{19}H_{18}O_3$: C, 77.53; H, 6.16%; *M*, 294.1256].

Ethyl 2-acetyl-2-methyl-5-oxohexanoate 3j

A mixture of the oxo ester **1j** (785 mg, 5.44 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (74 mg, 0.27 mmol) was stirred overnight at room temp., after which it was chromatographed on silica gel (hexane–MTB, 1 : 5; R_f 0.48) to afford **3j** as a colourless oil (910 mg, 4.25 mmol, 78%); ν_{max}/cm^{-1} (ATR) 2984m, 2941m, 1711vs, 1447m, 1423m, 1357s, 1296m, 1255s, 1227s, 1183s, 1167s, 1118s, 1103s and 1019m; δ_H(400 MHz, $CDCl_3$) 1.25 (t, *J* 7.2, 3 H, CH_3), 1.32 (s, 3 H, CH_3), 1.97–2.05 (m, 2 H, CH_2), 2.13 (s, 3 H, CH_3), 2.14 (s, 3 H, CH_3), 2.37–2.43 (m, 2 H, CH_2) and 4.14–4.20 (m, 2 H, OCH_2); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) 13.74 (CH_3), 18.95 (CH_3), 25.85 (CH_3), 28.10 (CH_2), 29.59 (CH_3), 38.26 (CH_2), 58.35 (C), 61.11 (OCH_2), 172.32 (C=O), 204.99 (C=O) and 206.94 (C=O); *m*/*z* (EI, 70 eV), 214 (0.1%) [M^+], 172 (77) [$M + H^+ - COMe$], 144 (14) [$M^+ - CH_2CHCOMe$], 126 (38) [$M^+ - CH_2CHCMe - H_2O$], 115 (72) [$MeCOC(Me)COO^+$], 98 (100) [$MeCOC(Me)CO^+$] and 87 (57) [$CH_2COOCH_2Me^+$] [Found: C, 61.66; H, 8.46%; M (HRMS), 214.1194. Calc. for $C_{11}H_{18}O_4$: C, 61.66; H, 8.47%; *M*, 214.1205].

3-Acetyl-3-methylhepta-2,6-dione 3k

A mixture of the dione **1k** (623 mg of a 85% containing mixture;[28] *i.e.* 530 mg, 4.64 mmol), the enone **2a** (0.500 ml, 6.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (74 mg, 0.27 mmol) was stirred overnight at room temp., after which all the volatile materials were removed *in vacuo* (2 h; to remove 3,3-dimethylpentane-2,4-dione, which was the contaminant of the starting material **1k**[28]), and the residue was chromatographed on silica gel (hexane–MTB, 1 : 5; R_f 0.33) to yield **3k** as a colourless oil (721 mg, 3.91 mmol, 84%); ν_{max}/cm^{-1} (ATR) 2977m, 2938m, 1715vs, 1697vs, 1423m, 1358s, 1293m, 1209m, 1167m, 1099m, 967m and 920m; δ_H(400 MHz, $CDCl_3$) 1.31 (s, 3 H, 3-CH_3), 2.04–2.08 (m, 2 H, 4-CH_2), 2.10 (s, 6 H, 1,1′-CH_3), 2.11 (s, 3 H, 7-CH_3) and 2.30–2.34 (m, 2 H, 5-CH_2); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 18.33 (CH_3), 26.30 (2 CH_3), 27.36 (CH_2), 29.68 (CH_3), 38.11 (CH_2), 65.05 (C) and 207.10 (3 C=O); *m*/*z* (EI, 70 eV), 184 (0.1%) [M^+], 142 (5) [$M^+ - CH_2CO$], 114 (2) [$M^+ - MeCOCH{=}CH_2$], 99 (8) [$MeCOCH_2COCH_2^+$] and 85 (100) [$MeCOCH_2CO^+$] [Found: M (HRMS), 184.1105. Calc. for $C_{10}H_{16}O_3$: *M*, 184.1099].

Ethyl 2-oxo-1-(1-phenyl-3-oxobutyl)cyclopentanecarboxylate 3l

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1a** (500 mg, 3.20 mmol), the enone **2b** (468 mg, 3.20 mmol) and $FeCl_3 \cdot 6\ H_2O$ (43 mg, 0.16 mmol) was stirred overnight at room temp., after which all the volatile materials were removed *in vacuo*, and the residue was chromatographed on silica gel (hexane–MTB, 1 : 1) to afford two fractions of **3l** containing two diastereoisomers: isomer B (174 mg, 0.58 mmol, 18%; R_f 0.39) and isomer A (697 mg, 2.31 mmol, 72%; R_f 0.35). Isomer A, colourless oil: ν_{max}/cm^{-1} (ATR) 2979m, 2893w, 1748s, 1718vs, 1495m, 1453m, 1405m, 1365m, 1357m, 1315w, 1292m, 1224s, 1159s, 1143s, 1109m, 1022m and 704s; δ_H(400 MHz, $CDCl_3$) 1.19 (t, *J* 7.1, 3 H, CH_3), 1.45–1.54 (m, 1 H, C*H*H), 1.66–1.84 (m, 2 H, CH_2), 1.92–2.05 (m, 1 H, CH*H*), 1.98 (s, 3 H, 4′-CH_3), 2.31–2.42 (m, 2 H, CH_2), 2.73 (dd, *J* 16, 2.6, 1 H, 2′-C*H*H), 3.29 (dd, *J* 16, 11, 1 H, 2′-CH*H*), 3.96 (dd, *J* 11, 2.6, 1 H, 1′-CH), 4.04–4.19 (m, 2 H, OCH_2) and 7.16–7.27 (m, 5 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.94 (CH_3), 19.31 (CH_2), 30.18 (CH_3), 32.20 (CH_2), 39.42 (CH_2), 44.42 (CH), 45.68 (CH_2), 61.62 (CH_2), 64.02 (C), 127.26 (CH), 128.41 (2 CH), 129.08 (2 CH), 139.49 (C), 170.65 (C=O), 206.12 (C=O) and 215.18 (C=O); *m*/*z* (EI, 70 eV), 302 (7%) [M^+], 284 (37) [$M^+ - H_2O$], 256 (23) [$M^+ - CO - H_2O$], 229 (66) [$M^+ - COOEt$], 211 (100) [$M^+ - C_7H_7$], 187 (29) [$M^+ - COOEt - COCH$], 186 (28) [$M^+ - COOEt - COCH_2$], 185 (52) [$M^+ - COOEt - COMe$], 171 (46) [$M^+ - PhCHCHCO$], 156 (82) [$M^+ - PhCHCHCOMe$], 147 (42) [$PhCHCHCOMe + H^+$] and 43 (43) [$COMe^+$] [Found: C, 71.51; H, 7.33%; M (HRMS), 302.1509. Calc. for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33%; *M*, 302.1518]. Isomer B, colourless oil: ν_{max}/cm^{-1} (ATR) 2978m, 1747s, 1715vs, 1495m, 1453m, 1365m, 1356m, 1281m, 1222s, 1141s, 1109m, 1021m and 704s; δ_H(400 MHz, $CDCl_3$) 1.24 (t, *J* 7.2, 3 H, CH_3), 1.68–1.86 (m, 3 H, CH_2), 1.97–2.05 (m, 1 H, C*H*H), 2.02 (s, 3 H, 4′-CH_3), 2.16–2.27 (m, 1 H, CH*H*), 2.39–2.47 (m, 1 H, CH*H*), 2.95–3.07 (m, 2 H, 2′-CH_2), 4.03 (dd, *J* 9.1, 5.5, 1 H, 1′-CH), 4.10–4.22 (m, 2 H, OCH_2) and 7.16–7.28 (m, 5 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.71 (CH_3), 19.06 (CH_2), 29.59 (CH_3), 29.68 (CH_2), 38.04 (CH_2), 43.03 (CH), 44.77 (CH_2), 61.32 (CH_2), 63.90 (C), 126.94 (CH), 127.99 (2 CH), 129.43 (2 CH), 138.54 (C), 169.63 (C=O), 206.03 (C=O) and 212.84 (C=O); *m*/*z* (EI, 70 eV), 302 (4%) [M^+], 284 (28) [$M^+ - H_2O$], 256 (22) [$M^+ - CO - H_2O$], 229 (50) [$M^+ - COOEt$], 211 (98) [$M^+ - C_7H_7$], 187 (31) [$M^+ - COOEt - COCH$], 186 (30) [$M^+ - COOEt - COCH_2$], 185 (56) [$M^+ - COOEt - COMe$], 171 (52) [$M^+ - PhCH{-}CHCO$], 156 (78) [$M^+ - PhCHCHCOMe$], 147 (49) [$PhCH{-}CHCOMe + H^+$], 91 (28) [$C_7H_7^+$] and 43 (100) [$COMe^+$] [Found: C, 71.70; H, 7.33%; M (HRMS), 302.1516. Calc. for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33%; *M*, 302.1518].

Ethyl 2-oxo-1-(1,3-diphenyl-3-oxopropyl)cyclopentanecarboxylate 3m

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1a** (500 mg, 3.20 mmol), the enone **2c** (660 mg, 3.20 mmol) and $FeCl_3 \cdot 6\ H_2O$ (8.7 mg, 0.032 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 2 : 1; R_f 0.25) to afford **3m** as an oil (1.13 g, 3.09 mmol, 96%) comprising two diastereoisomers (ratio A/B = 53 : 47 by ^1H NMR), which were not separated; ν_{max}/cm^{-1} (ATR) 3061w, 3030w, 2979m, 2891w, 1748vs, 1723vs, 1687vs, 1597m, 1580w, 1496w, 1448m, 1404w, 1366w, 1293w, 1224s, 1178w, 1144m, 1109w, 1033w, 1017w, 1002w, 921w, 860w, 749m, 691m and 702m; δ_H(400 MHz, $CDCl_3$) 1.19 (t, *J* 7.1, 3 H, CH_3), 1.25 (t, *J* 7.1, 3 H, CH_3), 1.45–1.53 (m, 1 H), 1.73–1.90 (m, 4 H), 2.01 (dd, *J* 18.5, 9.0, 1 H), 2.07–2.14 (m, 2 H), 2.21–2.30 (m, 1 H), 2.37–2.44 (m, 2 H), 2.47–2.53 (m, 1 H), 3.31 (dd, *J* 17.1, *J* 2.7, 1 H, 2′-C*H*H), 3.57–3.66 (m, 2 H, 2′-CH_2), 3.94 (dd, *J* 17.1, *J* 10.8, 1 H, 2′-CH*H*), 4.05–4.22 (m, 6 H, 1′-CH and OCH_2), 7.15–7.29 (m, 10 H, ArH), 7.39–7.43 (m, 4 H, ArH), 7.49–7.53 (m, 2 H, ArH) and 7.89–7.91 (m, 4 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.74 (CH_3), 13.77 (CH_3), 19.14 (CH_2), 19.18 (CH_2), 30.12 (CH_2), 32.40 (CH_2), 38.08 (CH_2), 39.34 (CH_2), 39.90 (CH_2), 40.51 (CH_2), 43.34 (CH), 44.48 (CH), 61.39 (2 OCH_2), 63.85 (C), 64.04 (C), 126.85 (CH), 126.95 (CH), 127.76 (2 CH), 127.80 (2 CH), 127.93 (2 CH), 128.11 (2 CH), 128.21 (2 CH), 128.24 (2 CH), 128.99 (2 CH), 129.52 (2 CH), 132.65 (CH), 132.67 (CH), 136.62 (C), 136.64 (C), 138.80 (C), 139.45 (C), 169.90 (C=O), 170.70 (C=O), 197.35 (C=O), 197.64 (C=O), 212.99 (C=O) and 215.21 (C=O); *m*/*z* (EI, 70 eV), 364 (2%) [M^+], 336 (6) [$M^+ - CO$], 319 (7) [$M^+ - OEt$], 291 (8) [$M^+ - COOEt$], 273 (54) [$M^+ - C_7H_7$], 245 (12) [$M^+ - PhCOCH_2$], 209 (57) [$PhCHCH_2COPh^+$], 208 (55) [$PhCHCH{-}COPh^+$], 207 (68) [$PhCHCCOPh^+$], 155 (6) [$M^+ - PhCHCH_2{-}COPh$], 143 (9) [$PhCCCOCH_2^+$], 115 (14) [$PhCCCH_2^+$], 105 (100) [$PhCO^+$], 103 (16) [$PhCHCH^+$], 91 (7) [$C_7H_7^+$] and 77 (58) [$C_6H_5^+$] [Found: C, 75.74; H, 6.75%; M (HRMS), 364.1675. Calc. for $C_{23}H_{24}O_4$: C, 75.80; H, 6.64%; *M*, 364.1675].

Ethyl 2-oxo-1-(2-phenyl-3-oxobutyl)cyclopentanecarboxylate 3n

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1a** (468 mg, 3.00 mmol), the enone **2d** (439 mg, 3.00 mmol), and $FeCl_3 \cdot 6\ H_2O$ (41 mg, 0.15 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1 : 1) to afford one fraction of **4b** as a colourless oil (88 mg, 0.30 mmol, 20%; R_f 0.58) and two fractions of **3n** containing two diastereoisomers; isomer B (163 mg, 0.54 mmol, 18%; R_f 0.42) and isomer A (490 mg, 1.62 mmol, 54%; R_f 0.35). Isomer A, a col-

ourless oil: ν_{max}/cm^{-1} (ATR) 2978m, 2937w, 1749vs, 1714vs, 1454m, 1405w, 1355m, 1276m, 1231s, 1190s, 1155s, 1111s, 1029m, 763m and 701s; δ_H(400 MHz, $CDCl_3$) 1.13 (t, *J* 7.1, 3 H, CH_3), 1.72 (dt, *J* 13.0, *J* 7.7, 1 H), 1.82–1.92 (m, 2 H), 2.02 (s, 3 H, CH_3), 2.13–2.23 (m, 2 H), 2.30 (dt, *J* 19.1, 7.3, 1 H), 2.45 (dd, *J* 12.5, 6.1, 1 H), 2.52 (dd, *J* 14.5, 7.1, 1 H), 3.81–3.91 (m, 2 H), 3.92–4.01 (m, 1 H, OC*H*H) and 7.12–7.30 (m, 5 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.72 (CH_3), 19.09 (CH_2), 28.82 (CH_3), 32.79 (CH_2), 34.97 (CH_2), 37.10 (CH_2), 55.43 (CH), 59.79 (C), 61.19 (OCH_2), 127.19 (CH), 128.14 (2 CH), 128.71 (2 CH), 138.83 (C), 170.17 (C=O), 206.93 (C=O) and 213.55 (C=O); *m*/*z* (EI, 70 eV), 302 (3%) [M^+], 198 (10) [$M^+ - CH_2CHPh$], 185 (34) [$M^+ - CH_2CHPhCH$], 156 (100) [$M^+ - CH_2CHPhCOMe$] and 91 (11) [$C_7H_7^+$] [Found: C, 71.53; H, 7.37%; M (HRMS), 302.1515. Calc. for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33%; *M*, 302.1518].

Isomer B, colourless oil: ν_{max}/cm^{-1} (ATR) 2978m, 2938m, 1774vs, 1716vs, 1276m, 1229m, 1182m, 1161s, 1113m, 1029m, 1005m, 759m and 702s; δ_H(400 MHz, $CDCl_3$) 1.23 (t, *J* 7.2, 3 H, CH_3), 1.76–1.83 (m, 1 H), 1.91–2.01 (m, 2 H), 2.02 (s, 3 H, CH_3), 2.07–2.17 (m, 2 H), 2.29–2.33 (m, 2 H), 2.76 (dd, *J* 14.2, 8.8, 1 H), 4.09–4.15 (m, 3 H, CH, OCH_2) and 7.16–7.32 (m, 5 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.93 (CH_3), 19.55 (CH_2), 29.11 (CH_3), 35.87 (CH_2), 35.99 (CH_2), 38.02 (CH_2), 55.05 (CH), 59.22 (C), 61.23 (OCH_2), 127.16 (CH), 128.06 (2 CH), 128.88 (2 CH), 139.49 (C), 171.85 (C=O), 207.56 (C=O) and 215.83 (C=O); *m*/*z* (EI, 70 eV), 302 (2%) [M^+], 185 (18) [$M^+ - CH_2CHPhCH$], 157 (100) [$M^+ - CHCHPhCOMe$] and 128 (65), 111 (87) [Found: C, 71.21; H, 7.32%; M (HRMS), 302.1515. Calc. for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33%; *M*, 302.1518].

Ethyl 2-benzoyl-5-oxo-3-phenylhexanoate 3o

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1g** (577 mg, 3.00 mmol), the enone **2b** (439 mg, 3.00 mmol), and $FeCl_3 \cdot 6\ H_2O$ (8.1 mg, 0.030 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo*, and the residue was chromatographed on silica gel (hexane–MTB, 1:1) to afford two fractions of **3o** containing two diastereoisomers: isomer A (136 mg, 0.40 mmol, 13%; R_f 0.36) and isomer B (716 mg, 2.12 mmol, 71%; R_f 0.27). Analytically pure samples were obtained by crystallisation from hexane–CH_2Cl_2 (5:1) at −20 °C.

Isomer A, colourless crystals, mp 71–72 °C; ν_{max}/cm^{-1} (ATR) 2981m, 1730vs, 1720vs, 1685vs, 1597m, 1448m, 1366m, 1279s, 1258s, 1210s, 1185m, 1150s, 1027m, 986m, 759m, 739m, 701s and 690s; δ_H(400 MHz, $CDCl_3$) 0.88 (t, *J* 7.1, 3 H, CH_3), 2.00 (s, 3 H, 6-CH_3), 2.81–2.84 (m, 2 H, 4-CH_2), 3.78–3.85 (m, 2 H, OCH_2), 4.18–4.24 (m, 1 H, 3-CH), 4.80 (d, *J* 10.1, 1 H, 2-CH), 7.15–7.22 (m, 1 H, ArH), 7.24–7.33 (m, 4 H, ArH), 7.46–7.51 (m, 2 H, ArH), 7.58–7.61 (m, 1 H, ArH) and 8.04–8.07 (m, 2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.61 (CH_3), 30.24 (CH_3), 40.96 (CH), 47.68 (CH_2), 59.67 (CH), 61.40 (CH_2), 126.23 (CH), 128.44 (4 CH), 128.76 (4 CH), 133.79 (CH), 136.44 (C), 140.27 (C), 167.77 (C=O), 193.54 (C=O) and 206.47 (C=O); *m*/*z* (EI, 70 eV), 338 (4%) [M^+], 292 (42) [$M^+ - H - EtO$], 247 (78) [$M^+ - C_7H_7$], 233 (22) [$M^+ - PhCO$], 187 (49) [$M^+ - PhCO - EtO - H$], 147 (21) [$M^+ + H^+ - PhCO - CO_2 - COMe$], 105 (100) [$PhCO^+$] and 77 (70) [$Ph^+$] [Found: C, 74.41; H, 6.36%; M (HRMS), 338.1517. Calc. for $C_{21}H_{22}O_4$: C, 74.54; H, 6.55%; *M*, 338.1518].

Isomer B, colourless crystals, mp 163 °C; ν_{max}/cm^{-1} (ATR) 2980m, 2931m, 1734vs, 1719vs, 1685s, 1597m, 1581m, 1495m, 1448m, 1366m, 1358m, 1278m, 1254s, 1208m, 1175m, 1154s, 1096m, 1022m, 701s and 690m; δ_H(400 MHz, $CDCl_3$) 1.16 (t, *J* 7.2, 3 H, CH_3), 2.03 (s, 3 H, 6-CH_3), 2.97–3.00 (m, 2 H, 4-CH_2), 4.13 (q, *J* 7.1, 2 H, OCH_2), 4.15–4.22 (m, 1 H, 3-CH), 4.79 (d, *J* 9.6, 1 H, 2-CH), 7.08–7.10 (m, 1 H, ArH), 7.15–7.19 (m, 2 H, ArH), 7.21–7.26 (m, 2 H, ArH), 7.36–7.40 (m, 2 H, ArH), 7.48–7.52 (m, 1 H, ArH) and 7.80–7.83 (m, 2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.91 (CH_3), 30.29 (CH_3), 40.70 (CH), 47.26 (CH_2), 59.08 (CH), 61.66 (CH_2), 126.96 (CH), 128.12 (2 CH), 128.37 (2 CH), 128.48 (2 CH), 128.53 (2 CH), 133.32 (CH), 136.57 (C), 140.89 (C), 168.53 (C=O), 193.64 (C=O) and 206.38 (C=O); *m*/*z* (EI, 70 eV), 338 (1%) [M^+], 292 (16) [$M^+ - H - EtO$], 247 (36) [$M^+ - C_7H_7$], 233 (20) [$M^+ - PhCO$], 192 (22) [$M + H^+ - PhCO - CH_2CO$], 187 (55) [$M^+ - PhCO - EtO - H$], 147 (14) [$M + H^+ - PhCO - CO_2 - COMe$], 105 (100) [$PhCO^+$] and 77 (20) [$Ph^+$] [Found: C, 74.21; H, 6.51%; M (HRMS), 338.1522. Calc. for $C_{21}H_{22}O_4$: C, 74.54; H, 6.55%; *M*, 338.1518].

Ethyl 2-benzoyl-5-oxo-3,5-diphenylpentanoate 3p

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1g** (577 mg, 3.00 mmol), the enone **2c** (625 mg, 3.00 mmol), and $FeCl_3 \cdot 6\ H_2O$ (8.1 mg, 0.030 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1; R_f 0.37) to afford **3p** as a colourless solid (1.02 g, 2.55 mmol, 85%) as a mixture of two diastereoisomers (A/B = 78:22 by ^1H NMR). Only isomer A was obtained purely by crystallisation from hexane–CH_2Cl_2 (5:1) at −20 °C.

Isomer A, colourless crystals, mp 138 °C; ν_{max}/cm^{-1} (ATR) 3062m, 3029m, 2981m, 2906m, 1734vs, 1684vs, 1597s, 1579m, 1495m, 1448s, 1411m, 1367m, 1335s, 1261vs, 1215vs, 1181s, 1152s, 1096m, 1078m, 1034m, 1017s, 1001s, 981m, 749vs, 700s and 689vs; δ_H(400 MHz, $CDCl_3$) 0.88 (t, *J* 7.1, 3 H, CH_3), 3.30 (dd, *J* 16.1, 9.8, 1 H, 4-C*H*H), 3.49 (dd, *J* 16.0, 4.0, 1 H, 4-CH*H*), 3.78–3.86 (m, 2 H, OCH_2), 4.37–4.44 (m, 1 H, 3-CH), 4.92 (d, *J* 9.9, 1 H, 2-CH) and 7.03–8.10 (m, 15 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.56 (CH_3), 41.37 (CH), 42.94 (CH_2), 59.88 (CH), 61.34 (CH_2), 127.08 (CH), 128.09 (2 CH), 128.27 (2 CH), 128.44 (4 CH), 128.52 (2 CH), 128.76 (2 CH), 132.88 (CH), 133.74 (CH), 136.46 (C), 136.83 (C), 140.16 (C), 167.83 (C=O), 193.64 (C=O) and 197.92 (C=O); *m*/*z* (EI, 70 eV), 401 (0.5%) [$M + H^+$], 309 (78) [$M^+ - C_7H_7$], 295 (22) [$M^+ - PhCO$], 249 (82) [$M^+ - PhCO - EtO - H$], 209 (58) [$PhCOCH_2CHPh^+$], 105 (100) [$PhCO^+$] and 77 (67) [Ph^+] [Found: C, 77.76; H, 6.05%; M (HRMS), 400.1677. Calc. for $C_{26}H_{24}O_4$: C, 77.97; H, 6.04%; *M*, 400.1675].

Isomer B (identified in a mixture with isomer A): δ_H(400 MHz, $CDCl_3$) 1.16 (t, *J* 7.1, 3 H, CH_3), 3.54–3.57 (m, 2 H, 4-CH_2), 4.16–4.19 (m, 2 H, OCH_2), 4.37–4.44 (m, 1 H, 3-CH), 4.93 (d, *J* 9.6, 1 H, 2-CH) and 7.03–8.10 (m, 15 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.89 (CH_3), 41.05 (CH), 42.39 (CH_2), 59.13 (CH), 61.63 (CH_2), 126.82 (CH), 128.03 (2 CH), 128.17 (2 CH), 128.34 (4 CH), 128.37 (2 CH), 128.91 (2 CH), 132.72 (CH), 133.28 (CH), 134.84 (C), 136.58 (C), 140.89 (C), 168.63 (C=O), 193.80 (C=O) and 197.79 (C=O).

Ethyl 2-benzoyl-5-oxo-4-phenylhexanoate 3q

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1g** (577 mg, 3.00 mmol), the enone **2d** (439 mg, 3.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (41 mg, 0.15 mmol) was stirred overnight at room temp., after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1) to afford one fraction (R_f 0.58) **4b** as a colourless oil (75 mg, 0.26 mmol, 17%) and a second fraction (R_f 0.38) containing **3q** also as a colourless oil (751 mg, 2.22 mmol, 74%). Product **3q** consisted of two diastereoisomers (A/B = 57:43 by ^1H NMR), which were equilibrating and, thus, could not be separated; ν_{max}/cm^{-1} (ATR) 2980m, 1735vs, 1712vs, 1684vs, 1597m, 1493m, 1448m, 1355m, 1274m, 1228s, 1193s, 1183s, 1173s, 1156s, 1096m, 1028m, 766m, 752m, 701s, 690m and 668m; δ_H(400 MHz, $CDCl_3$) 1.12 (t, *J* 6.6, 3 H, CH_3), 1.16 (t, *J* 7.1, 3 H, CH_3), 1.99 (s, 3 H, CH_3), 2.05 (s, 3 H, CH_3), 2.25–2.35 (m, 2 H, 3-CH_2), 2.60–2.72 (m, 2 H, 3-CH_2), 3.77–3.82 (m, 2 H, 2 4-CH), 4.04–4.15 (m, 4 H, 2 OCH_2), 4.14 (t, *J* 7.1, 1 H, 2-CH), 4.22 (t, *J* 7.3, 1 H, 2-CH), 7.08–7.11 (m, 2 H, ArH), 7.17–7.20 (m, 2 H, ArH), 7.23–7.40 (m, 6 H, ArH), 7.41–7.46 (m, 3 H, ArH), 7.50–7.57 (m, 3 H, ArH), 7.69–7.71 (m, 2 H, ArH) and 7.92–7.95 (m,

2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.80 (CH_3), 13.86 (CH_3), 28.92 (CH_3), 29.09 (CH_3), 30.84 (CH_2), 30.91 (CH_2), 51.20 (CH), 51.55 (CH), 56.53 (CH), 56.64 (CH), 61.28 (2 OCH_2), 127.57 (CH), 127.75 (CH), 128.06 (2 CH), 128.16 (2 CH), 128.35 (2 CH), 128.40 (2 CH), 128.55 (2 CH), 128.79 (2 CH), 129.05 (2 CH), 129.13 (2 CH), 133.44 (2 CH), 135.54 (C), 135.88 (C), 137.60 (C), 137.77 (C), 169.54 (C=O), 169.65 (C=O), 194.94 (C=O), 195.24 (C=O), 206.97 (C=O) and 207.35 (C=O); *m/z* (EI, 70 eV), 338 (2%) [M^+], 295 (40) [$M^+ - MeCO$], 278 (6) [$M + H^+ - MeCO - H_2O$], 192 (100) [$M^+ - MeCOCPhCH_2$], 146 (8) [$MeCOCPhCH_2^+$], 105 (86) [$PhCO^+$] and 77 (16) [$C_6H_5^+$] [Found: C, 74.14; H, 6.28%; M (HRMS), 338.1515. Calc. for $C_{21}H_{22}O_4$: C, 74.54; H, 6.55; *M* 338.1518].

Ethyl 2-acetyl-5-oxo-3-phenylhexanoate 3r

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1f** (390 mg, 3.00 mmol), the enone **2b** (439 mg, 3.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (41 mg, 0.15 mmol) was stirred overnight at room temp., after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1; R_f 0.25) to afford **3r** as a colourless oil (630 mg, 2.28 mmol, 76%) which solidified in the refrigerator and consisted of two equilibrating diastereoisomers (A/B = 57:43 by ^1H NMR); ν_{max}/cm^{-1} (ATR) 2983m, 1738vs, 1714s, 1495m, 1454m, 1419m, 1357s, 1292sh, 1272m, 1243s, 1178m, 1152s, 1096m, 1022s, 758m and 701s; δ_H(400 MHz, $CDCl_3$) 0.95 (t, *J* 7.2, 3 H, CH_3), 1.25 (t, *J* 7.1, 3 H, CH_3), 1.96 (s, 3 H, CH_3), 1.99 (s, 3 H, CH_3), 2.00 (s, 3 H, CH_3), 2.25 (s, 3 H, CH_3), 2.77–2.79 (m, 2 H, 4-CH_2), 2.86–2.88 (m, 2 H, 4-CH_2), 3.88 (q, *J* 7.1, 2 H, OCH_2), 3.85–3.98 (m, 4 H, 2- and 3-CH), 4.17 (q, *J* 7.2, 2 H, OCH_2) and 7.15–2.28 (m, 10 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.27 (CH_3), 13.61 (CH_3), 29.03 (CH_3), 29.58 (CH_3), 29.85 (CH_3), 29.96 (CH_3), 39.77 (3-CH), 39.99 (3-CH), 47.06 (2 4-CH_2), 60.83 (OCH_2), 61.14 (OCH_2), 64.13 (2-CH), 64.88 (2-CH), 126.70 (CH), 126.80 (CH), 127.70 (2 CH), 127.76 (2 CH), 128.03 (2 CH), 128.27 (2 CH), 140.14 (C), 140.33 (C), 167.51 (C=O), 167.90 (C=O), 201.45 (C=O) 201.80 (C=O), 205.64 (C=O) and 205.97 (C=O); *m/z* (EI, 70 eV), 276 (1%) [M^+], 233 (17) [$M^+ - MeCO$], 230 (13) [$M^+ - EtOH$], 191 (12) [$M^+ - MeCO-CH_2 - CO$], 187 (100) [$M^+ - Me - HCOOEt$], 185 (68) [$M^+ - C_7H_7$], 177 (16) [$M^+ - MeCOCH_2 - CH_2CO$], 173 (26) [$M^+ - MeCOCH_2 - CO - H_2O$], 147 (32) [PhCHCHCOMe + H^+], 145 (54) [$PhCHCHCOMe^+ - H$], 131 (67) [$PhCHCHCO^+$], 103 (24) [$PhCHCH^+$] [Found: C, 69.72; H, 7.27%; M (HRMS), 276.1377. Calc. for $C_{16}H_{20}O_4$: C, 69.55; H, 7.30; *M*, 276.1362].

Ethyl 2-acetyl-5-oxo-4-phenylhexanoate 3s

A mixture of $CHCl_3$ (0.5 ml), the oxo ester **1f** (390 mg, 3.00 mmol), the enone **2d** (439 mg, 3.00 mmol) and $FeCl_3 \cdot 6\ H_2O$ (41 mg, 0.15 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1) to afford one fraction (R_f 0.58) containing **4b** as a colourless oil (101 mg, 0.35 mmol, 23%) and a second fraction (R_f 0.21) containing **3s** as a colourless oil (381 mg, 1.38 mmol, 46%). Product **3s** consisted of two diastereoisomers (A/B = 55:45 by ^1H NMR), which were equilibrating and, thus, could not be separated; ν_{max}/cm^{-1} (ATR) 2982m, 2938m, 1739vs, 1712vs, 1494m, 1454m, 1357s, 1299m, 1244s, 1219s, 1152s, 1097m, 1029s, 958m, 759s and 702s; δ_H(400 MHz, $CDCl_3$) 1.20 (t, *J* 7.2, 3 H, CH_3), 1.23 (t, *J* 7.3, 3 H, CH_3), 1.99 (s, 6 H, 2 CH_3), 2.09 (s, 3 H, CH_3), 2.12–2.22 (m, 2 H, 3-CH_2), 2.15 (s, 3 H, CH_3), 2.44–2.55 (m, 2 H, 3-CH_2), 3.18 (dd, *J* 8.9, 5.1, 1 H, 2-CH), 3.29 (t, *J* 7.3, 1 H, 2-CH), 3.63–3.69 (m, 2 H, 2 4-CH), 4.06–4.19 (m, 4 H, 2 OCH_2), 7.11–7.14 (m, 4 H, ArH) and 7.26–7.32 (m, 6 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.88 (CH_3), 13.93 (CH_3), 28.58 (CH_3), 28.85 (CH_3), 28.96 (CH_3), 29.09 (CH_3), 29.60 (2 3-CH_2), 56.44 (2 CH), 56.88 (2 CH), 61.27 (OCH_2), 61.31 (OCH_2), 127.61 (CH), 127.67 (CH), 128.14 (2 CH), 128.21 (2 CH), 129.08 (4 CH), 137.42 (C), 137.66 (C), 169.28 (C=O), 169.31 (C=O), 202.55 (C=O), 202.65 (C=O), 206.88 (C=O) and 206.97 (C=O); *m/z* (EI, 70 eV), 276 (10%) [M^+], 161 (18) [$M^+ - 2\ MeCO - Et$], 159 (22) [$M^+ - HCOOEt - MeCO$], 145 (14) [$MeCO - CHPhCH_2^+$], 143 (16) [$M^+ - MeCO-CHPh$], 134 (22) [$PhCH_2COMe^+$], 130 (13) [$MeCOCH_2-COOEt^+$], 115 (14) [$MeCOCH_2COOCH_2^+$], 104 (100) [$PhCHCH_2^+$] and 91 (13) [$C_7H_7^+$] [Found: C, 69.55; H, 6.94; M (HRMS), 276.1355. Calc. for $C_{16}H_{20}O_4$: C, 69.55; H, 7.30; *M*, 276.1361].

2-Acetyl-6-methyl-2,5-diphenyl-3,4-dihydro-2*H*-pyran 4b

A mixture of absolute ethanol (0.3 ml), KOH (5 mg, 0.09 mmol), and the enone **2d** (292 mg, 2.00 mmol) was stirred for 2 d at room temp., after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1; R_f 0.58) to afford **4b** as a colourless oil (277 mg, 0.95 mmol, 95%); ν_{max}/cm^{-1} (ATR) 2919m, 1718vs, 1670s, 1599m, 1493s, 1447m, 1383m, 1351m, 1254m, 1211s, 1175s, 1131m, 1117s, 1073m, 1064m, 1031m, 989m, 757s and 699s; δ_H(400 MHz, $CDCl_3$) 1.99 (s, 3 H, CH_3), 2.09–2.12 (m, 1 H), 2.13–2.18 (m, 1 H), 2.18 (s, 3 H, CH_3), 2.28–2.37 (m, 1 H), 2.61–2.67 (m, 1 H), 7.11–7.14 (m, 2 H, ArH), 7.18–7.22 (m, 1 H, ArH), 7.26–7.34 (m, 3 H, ArH), 7.37–7.41 (m, 2 H, ArH) and 7.52–7.55 (m, 2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 18.06 (CH_3), 24.35 (CH_3), 24.72 (CH_2), 29.93 (CH_2), 85.69 (C), 111.34 (=C), 124.97 (2 CH), 126.11 (CH), 127.76 (CH), 128.00 (2 CH), 128.47 (2 CH), 128.65 (2 CH), 139.16 (C), 141.25 (C), 145.77 (=C) and 208.91 (C=O); *m/z* (EI, 70 eV), 292 (8%) [M^+], 249 (100) [$M^+ - MeCO$], 204 (52) [$M^+ - 2\ MeCO$], 129 (10) [$PhCCH_2CH_2C^+$] and 105 (50) [$PhCO^+$] [Found: C, 81.98; H, 6.68%; M (HRMS), 292.1455. Calc. for $C_{20}H_{20}O_2$: C, 82.16; H, 6.89%; *M*, 292.1462].

Ethyl 2-hydroxy-4-oxo-2,6-diphenylcyclohexanecarboxylate 5a

A mixture of absolute ethanol (1 ml), KOH (5 mg, 0.09 mmol), the oxo ester **1g** (577 mg, 3.00 mmol) and the enone **2b** (439 mg, 3.00 mmol) was stirred overnight at 50 °C, after which all the volatile materials were removed *in vacuo* to leave **5a** as a colourless solid (1.01 g, 3.00 mmol, 100%), which was purified by crystallisation from hexane–CH_2Cl_2 (1:1) at −20 °C; this afforded colourless crystals, mp 211 °C; ν_{max}/cm^{-1} (ATR) 3354s, 1718vs, 1495m, 1455m, 1447m, 1374m, 1346m, 1302m, 1256m, 1222m, 1179m, 1143m, 1067m, 1030m, 750s, 699s and 668m; δ_H(400 MHz, $CDCl_3$) 0.53 (t, *J* 7.14, 3 H, CH_3), 1.64 (s, br, 1 H, OH), 2.70–2.82 (m, 4 H, 3-CH_2 and 5-CH_2), 3.52–3.55 (m, 2 H, OCH_2), 3.72–3.87 (m, 1 H, 6-CH), 4.44 (d, *J* 2.78, 1 H, 1-CH), 7.24–7.37 (m, 8 H, ArH) and 7.49–7.52 (m, 2 H, ArH); $^{13}C\{^1H\}$ NMR (50 MHz, $CDCl_3$) δ 13.23 (CH_3), 43.28 (6-CH), 47.38 (CH_2), 53.98 (CH_2), 56.64 (1-CH), 60.60 (OCH_2), 77.28 (2-C), 124.57 (2 CH), 127.51 (2 CH), 127.57 (2 CH), 128.43 (2 CH), 128.74 (2 CH), 140.28 (C), 144.13 (C), 174.17 (C=O) and 205.88 (C=O); *m/z* (EI, 70 eV), 338 (4%) [M^+], 247 (25) [$M^+ - C_7H_7$], 177 (39) [$EtOCCH_2CHPh^+$], 162 (92) [$PhCHCH_2CO_2CH_2^+$], 146 (19) [$CH_2(CO)CH_2CHPh^+$], 131 (38) [$COCHCHPh^+$], 105 (199) [$PhCO^+$] and 77 (24) [$C_6H_5^+$] [Found: C, 74.49; H, 6.51%; M (HRMS), 338.1526. Calc. for $C_{21}H_{22}O_4$: C, 74.54; H, 6.55%; *M*, 338.1518].

Ethyl 4-hydroxy-4-methyl-8-oxo-2-phenylbicyclo[3.2.1]octane-1-carboxylate 5b

A mixture of absolute ethanol (1 ml), the oxo ester **1a** (469 mg, 3.00 mmol), the enone **2b** (439 mg, 3.00 mmol) and KOH (17 mg, 0.30 mmol) was stirred for 12 h at 50 °C, after which all the volatile materials were removed *in vacuo*. The residue was chromatographed on silica gel (hexane–MTB, 1:1) to afford four fractions the first containing a mixture of starting materials **1a** and **2b** (63 mg; R_f *ca.* 0.5), the second isomer B of **3l** (168 mg, 0.556 mmol, 19%; R_f 0.39), the third isomer A of **3l** (19 mg, 0.064 mmol, 2%; R_f 0.35) and finally the cyclic product

5b (446 mg, 1.48 mmol, 49%; R_f 0.20), a colourless solid, mp 142–143 °C (decomp.); ν_{max}/cm^{-1} (ATR) 3488s, 2970s, 2935s, 1756vs, 1722vs, 1497m, 1453m, 1368m, 1299m, 1271s, 1203m, 1130m, 1072m and 1022m; δ_H(400 MHz, $CDCl_3$) 1.08 (t, *J* 7.16, 3 H, CH_3), 1.36 (s, 3 H, CH_3), 1.73 (ddd, *J* 13.9, 10.9, 4.9, 1 H, 7-H), 1.85 (ddd, *J* 14.5, 5.01, 0.8, 1 H, 6-H), 2.03–2.15 (m, 3 H, OH, 6-H, 3-H), 2.35–2.43 (m, 2 H, 2-H, 7-H), 2.55–2.64 (m, 1 H, 3-H), 3.99 (dd, *J* 13.1, 4.8, 1 H, 5-H), 4.01–4.07 (m, 2 H, OCH_2) and 7.19–7.27 (m, 5 H, ArH); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 50 MHz) δ 13.93 (CH_3) 20.09 (CH_2), 20.67 (CH_2), 27.75 (CH_3), 39.48 (CH_2), 46.66 (CH), 56.61 (CH), 61.01 (CH_2), 61.23 (C), 77.64 (C), 127.09 (CH), 128.18 (2 CH), 128.29 (2 CH), 139.98 (C), 169.39 (C=O) and 209.44 (C=O); *m/z* (EI, 70 eV), 302 (8%) [M^+], 284 (12) [$M^+ - H_2O$], 274 (7) [$M^+ - CO$], 256 (11) [$M^+ - CH - H_2O$], 244 (9) [$M^+ - Me_2CO$], 229 (13) [$M^+ - COOEt$], 211 (66) [$M^+ - C_7H_7$], 156 (100) [$M^+ - PhCHCHCOMe$], 104 (47) [$PhCH{=}CH^+$], 91 (22) [$C_7H_7^+$] and 55 (15) [CH_2CHCO^+] [Found: M (HRMS), 302.1523. Calc. for $C_{18}H_{22}O_4$: *M*, 302.1518].

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References

1 D. A. Oare and C. H. Heathcock, in *Topics in Stereochemistry*, ed. E. L. Eliel and S. H. Wilen, Wiley-Interscience, New York, 1989, vol. 19, p. 227.
2 M. Shibasaki, H. Sasai and T. Arai, *Angew. Chem.*, 1997, **109**, 1290; *Angew. Chem.*, *Int. Ed. Engl.*, 1997, **36**, 1236.
3 F. Bonadies, A. Lattanzi, L. R. Orelli, S. Pesci and A. Scettri, *Tetrahedron Lett.*, 1993, **34**, 7649; E. Keller and B. L. Feringa, *Tetrahedron Lett.*, 1996, **37**, 1879; A. Soriente, A. Spinella, M. De Rosa, M. Giordano and A. Scettri, *Tetrahedron Lett.*, 1997, **38**, 289.
4 (*a*) C. P. Fei and T. H. Chan, *Synthesis*, 1982, 467; (*b*) H. Brunner and B. Hammer, *Angew. Chem.*, 1984, **96**, 305; *Angew. Chem.*, *Int. Ed. Engl.*, 1984, **32**, 312; (*c*) P. Kocovsky and D. Dvorak, *Tetrahedron Lett.*, 1986, **27**, 5015.
5 J. H. Nelson, P. N. Howells, G. C. DeLullo, G. L. Landen and R. A. Henry, *J. Org. Chem.*, 1980, **45**, 1246.
6 J. Christoffers, *J. Chem. Soc.*, *Chem. Commun.*, 1997, 943.
7 P. Laszlo, M.-T. Montaufier and S. L. Randraimahefa, *Tetrahedron Lett.*, 1990, **34**, 4867.
8 Literature cited in *Gmelins Handbuch der Anorganischen Chemie*, Eisen, Verlag Chemie, Berlin, 1932, vol. 59 B, pp. 554.
9 W. G. Dauben and J. W. McFarland, *J. Am. Chem. Soc.*, 1960, **82**, 4245.
10 K. Alder, H. Offermanns and E. Rüden, *Chem. Ber.*, 1941, **74**, 905.
11 A. S. Dreiding and A. J. Tomasewski, *J. Am. Chem. Soc.*, 1955, **77**, 411.
12 H. Henecka, *Chem. Ber.*, 1948, **81**, 179.
13 N. C. Ross and R. Levine, *J. Org. Chem.*, 1964, **29**, 2346.
14 H. Plieninger and T. Suehiro, *Chem. Ber.*, 1956, **89**, 2789.
15 H. Wynberg and R. Helder, *Tetrahedron Lett.*, 1975, 4057.
16 R. N. Lacey, *J. Chem. Soc.*, 1960, 1625.
17 Y. L. Chow, S.-S. Wang and X.-E. Cheng, *Can. J. Chem.*, 1993, **71**, 846.
18 S. Terashima, S. Sato and K. Koga, *Tetrahedron Lett.*, 1979, 3469.
19 W. Wilson and Z.-Y. Kyi, *J. Chem. Soc.*, 1952, 1321; A. F. Renaldo and H. Ito, *Synth. Commun.*, 1987, **17**, 1823.
20 W. Dieckmann and K. von Fischer, *Chem. Ber.*, 1911, **44**, 966.
21 E. D. Bergmann, S. Blumberg, P. Bracha and S. Epstein, *Tetrahedron*, 1964, **20**, 195; G. N. Walker, *J. Am. Chem. Soc.*, 1955, **77**, 3664.
22 A. Garcia-Raso, J. Garcia-Raso, B. Campaner, R. Mestres and J. V. Sinisterra, *Synthesis*, 1982, 1037.
23 W. S. Rapson, *J. Chem. Soc.*, 1936, 1626.
24 R. Connor and D. B. Andrews, *J. Am. Chem. Soc.*, 1934, **56**, 2713.
25 R. W. Hoffmann, *Angew. Chem.*, 1992, **104**, 1147; *Angew. Chem.*, *Int. Ed. Engl.*, 1992, **31**, 1124; R. W. Hoffmann, *Chem. Rev.*, 1989, **89**, 1841.
26 C. A. M. Fraga and E. J. Barreiro, *Synth. Commun.*, 1995, **25**, 1133.
27 D. H. Grayson and M. R. J. Tuite, *J. Chem. Soc.*, *Perkin Trans. 1*, 1986, 2137.
28 A. W. Johnson, E. Markham and R. Price, *Org. Synth.*, 1973, Coll. Vol. 5, 785.
29 T. Sakai, S. Matsumoto, S. Hidaka, N. Imajo, S. Tsuboi and M. Utaka, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 3473.

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