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Synthesis of 2,6-disubstituted dihydropyrans via an efficient $BiBr_3$-initiated three component, one-pot cascade

Robert J. Hinkle *, Yajing Lian, Lee C. Speight, Heather E. Stevenson, Melissa M. Sprachman, Lauren A. Katkish, M. Christa Mattern

Department of Chemistry, The College of William & Mary, PO Box 8795, Williamsburg, VA 23187-8795, USA

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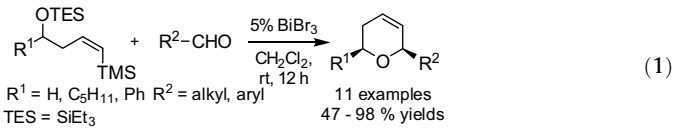
ABSTRACT

The rapid synthesis of *cis*-2,6-disubstituted dihydropyrans is achieved in a three-component, one-pot cascade reaction. $BiBr_3$-mediated addition of ketene silyl acetals or silyl enol ethers to β,γ-unsaturated *cis*-4-trimethylsilyl-3-butenal provides a Mukaiyama aldol adduct containing a vinylsilane moiety tethered to a silyl ether. Addition of a second aldehyde initiates a domino sequence involving intermolecular addition followed by an intramolecular silyl-modified Sakurai (ISMS) reaction. Isolated yields of this one-pot reaction vary from 44 to 80% and all compounds were isolated as the *cis*-diastereomers (10 examples).

1. Introduction

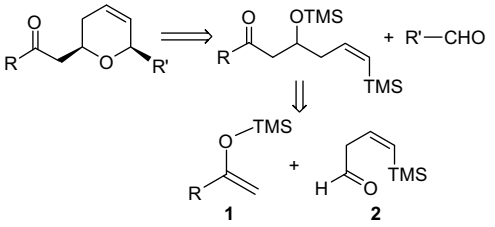
In efforts to reduce environmental impacts, increase atom economy as well as overall efficiency and convergence of experimental protocols, one-pot, multi-component reactions (MCRs)[1] have become increasingly common in organic synthesis. Efforts toward a number of natural products have resulted in the development of several protocols in which formation of an initial adduct is required to provide the substrate for a subsequent reaction. The literature has alternatively referred to such processes as tandem, multi-component, cascade, or domino reactions, although the precise meaning of each adjective has not been entirely consistent.[2]



(1)

As part of a program to further develop the uses of environmentally-benign[3,4] Bi(III) compounds in organic synthesis, we recently described[5] the $BiBr_3$-initiated intermolecular addition followed by intramolecular silyl-modified Sakurai reaction (ISMS) [6,7] toward 2,6-disubstituted dihydropyrans (DHPs) with *cis*-diastereoselectivity (Eq. 1). Similar DHPs were either present in, or could be used as intermediates toward syntheses of a number of biologically active natural products such as ambruticin 1,[8] the phorboxazoles,[9] leucascandrolide[10], kendomycin,[11] neopeltolide,[12] the clavisolides,[13] and the diospongins.[14] The prevalence of DHPs, and derivatives thereof, has led to a large number of concise and selective methods for their synthesis.[15–18]

More specifically, the utility of a DHP moiety attached to the α-position of a carbonyl compound[19] prompted us to further investigate a three-component, one-pot cascade reaction involving an initial Mukaiyama aldol reaction followed by an addition/ISMS sequence as shown in the retrosynthetic analysis below (Scheme 1). Given how rapidly molecular complexity is increased in this short sequence, we examined the utility of several silane nucleophiles, **1**, and aldehydes (R′CHO). Herein, we report further examples of this multi-component, one pot reaction and details of our optimization studies.



Scheme 1. Retrosynthetic analysis of 2,6-disubstituted DHPs.

2. Results and discussion

In order to evaluate the feasibility of the first step of the three-component process, we prepared aldehyde, (*Z*)-**2**, in two, straightforward steps from commercially-available 4-trimethylsilyl-3-butyn-1-ol.[20]

* Corresponding author. Tel.: +1 757 221 1501; fax: +1 757 221 2715.
E-mail address: rjhink@wm.edu (R.J. Hinkle).

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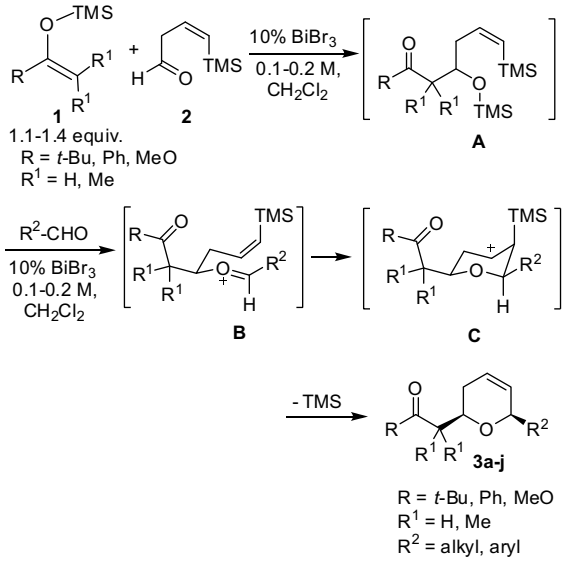
Reduction under nickel catalyzed conditions (P-2)[16k] was most convenient as it led to the best (*Z*):(*E*) ratios (>95:5) with little or no over-reduction to the alkane. As expected, the resulting β,γ-unsaturated aldehyde, **2**,[5] is particularly sensitive, and Dess–Martin periodinane[21] was the only oxidant that afforded the desired substrate in sufficient purity to study the three-component sequence. We chose to focus on using the (*Z*)-vinylsilane due to recent work by Meilert and Brimble[22] as well Dobbs et al.[23] showing that the *cis*-vinylsilane isomers efficiently participated in intramolecular reactions.

The initial Mukaiyama aldol[24–26] between **2** and the commercially-available methyl trimethylsilyldimethyl-ketene acetal (**1**; R=OMe, R^1=H) readily occurred at room temperature (Scheme 2) in the presence of 10 mol % $BiBr_3$ in CH_2Cl_2 (~0.1 M). Crude ^1H NMR spectroscopic analyses and TLC indicated that the initial Mukaiyama aldol reaction cleanly affords the sensitive silylated aldol adduct, **A**, which is an effective nucleophile for the second addition/silyl-Prins step (ISMS).[5] Although the free alcohol corresponding to **A** could be isolated by column chromatography, in practice, we carried **A** onto the next step without isolation or purification. Mukaiyama aldol reactions involving Bi(III) are also efficient in CH_3CN, but we chose CH_2Cl_2 as the solvent since our previous studies indicated that the intermolecular addition and ISMS occurred more efficiently in this solvent versus CH_3CN.[5] Addition of a second aldehyde (R^2CHO) and 10 mol % more $BiBr_3$ results in an intermolecular addition of **A** to the second aldehyde (R^2CHO) to afford the *E*-oxocarbenium ion, **B**. An intramolecular silyl-Prins reaction then affords **3a**–**3j** via the intermediate stabilized cation, **C**.



Scheme 2. Reaction sequence for the three-component, one-pot synthesis of dihydropyrans.

When using 1.1–1.4 equiv of ketene acetal (Table 1, entries 1–4 and 11), the initial aldol reaction occurs very rapidly at temperatures down to −20 °C in CH_2Cl_2 or CH_3CN. During optimization, we did find that the single most important variable for clean formation of the Mukaiyama adduct, **A**, was the specific commercial samples of ketene silyl acetal. Although we examined individual samples by ^1H and ^{13}C NMR spectroscopy and found no significant impurities, some reactions required up to 1.4 equiv of the ketene silyl acetal nucleophile whereas another was effectively used with as little as 1.1 equivalents. This is most likely due to variations in trace water content and competing hydrolysis reactions during the Mukaiyama aldol step.

In all cases in which silyl enol ethers were used instead of the more nucleophilic ketene silyl acetals[27] at the same concentration (entry 3 vs 5), the reaction was much slower at room temperature and did not proceed to completion unless the $BiBr_3$ was activated by sonication in the presence of NaI as reported by Le Roux et al.[28] This presumably affords the more reactive BiI_3 salt in situ. We later found, however, that activation and sonication could be avoided, albeit less efficiently, if the aldol was conducted at ~0.2 M instead of ~0.1 M without NaI activation (entries 6 vs 7 and 8 vs 9).

In all cases where the hydrogens adjacent to the oxygen in the ring system could be sufficiently separated in the ^1H NMR spectrum, qualitative ^1H NOE spectra indicated that the *cis*-isomers[29] of DHPs **3a**–**j** were the only diastereomers observed in agreement with other silyl-Prins type cyclizations (Fig. 1).[22,23]

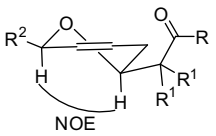
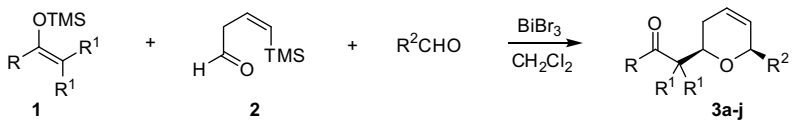


Figure 1. Observed qualitative NOE enhancement.

Table 1
Three-component, one-pot reaction to 2,6-disubstituted dihydropyrans



Entry	R	R^1	R^2	Product	dr (*cis:trans*)[a]	Yield[b] (%)
1	MeO–	–Me	$PhCH_2$–	**3a**	>99:1	64
2	MeO–	–Me	*i*-Pr–	**3b**	>99:1	53
3	MeO–	–Me	*n*-C_5H_{11}–	**3c**	>99:1	64
4	MeO–	–Me	*ortho*-$CHOC_6H_4$–	**3d**	>99:1	55
5	Ph–	–H	*n*-C_5H_{11}–	**3e**	>99:1	76[c]
6	Ph–	–H	1-ethylpropyl–	**3f**	>19:1	66[c]
7	Ph–	–H	1-ethylpropyl–	**3f**	>19:1	56[d]
8	*tert*-Bu–	–H	*n*-C_7H_{15}–	**3g**	>19:1	80[c]
9	*tert*-Bu–	–H	*n*-C_7H_{15}–	**3g**	>19:1	55[d]
10	*tert*-Bu–	–H	$PhCH_2CH_2$–	**3h**	>19:1	52[d]
11	MeO–	–Me	$PhCH_2CH_2$–	**3i**	>19:1	63
12	Ph–	–H	Ph–	**3j**	>19:1	44[d]

[a] Diastereoselectivities were determined by ^1H NMR or GC–MS analysis of crude reaction mixtures prior to chromatographic separation.
[b] Yields are reported for pure, isolated *cis*-compounds characterized by ^1H NMR and ^{13}C NMR spectroscopy, IR spectrometry and HRMS or elemental analysis.
[c] Initial Mukaiyama aldol carried out at ~0.1 M with added NaI and sonication.
[d] Initial Mukaiyama aldol carried out at ~0.2 M with neither added NaI, nor sonication.

We were particularly interested in syntheses using β,β-unsubstituted enol ethers as nucleophiles since these resulting intermediates and products might be prone to aldol reactions or eliminations via putative enols or enolates. We were gratified to isolate several products with enolizable hydrogens α- to the carbonyl moiety; these were obtained in yields ranging from 52% to 80% (entries 5–10). The lowest yield was observed for product **3j** (entry 12) even though both the initial Mukaiyama aldol and the subsequent addition/silyl-Prins reactions appeared clean by TLC analysis and ^{1}H NMR spectroscopic evaluation of the crude product. This particular product appeared less stable than the other nine and prolonged reaction times led to complex mixtures while storage at room temperature also caused decomposition. This instability is likely due to the fact that the phenyl substituent (R^2) promotes ring opening under the reaction conditions via a benzylic cation.

Although we attempted cyclizations using (*E*)-vinylsilanes due to reports that the *(E)*-vinylsilanes provided *trans*-2,6-diastereomers,[16k] we found that in the two-component case analogous to that in Eq. 1, only trace quantities of cyclization products were afforded (GC–MS) using (*E*)-vinylsilanols.[5] This result is consistent with the stereoelectronic stabilization of the developing cation by the axial trimethylsilyl moiety in intermediates **B** and **C** (Scheme 2) as described by Speckamp[16k] and Roush[16i] for DHPs as well as Overman[30] and Tanner[31] for iminium ion cyclizations.

The exact role(s) of Bi(III) compounds as catalysts in organic synthesis is still debated in numerous papers. Whereas BiX_3 compounds are often described as weak Lewis acids,[3,32,33] and investigators have attributed their reactivity to this property, we[34] and others[35] believe that BiX_3 species are progenitors of Brønsted acids and that these contribute to the activities of BiX_3 salts. Even in cases where Brønsted acids have been shown to be involved, their specific role is not always clear,[36,37,38] especially in the presence of Lewis acids.[39]

Bismuth(III) halides are known to rapidly hydrolyze to H–X and bismuthoxy halides (X–Bi=O) which are insoluble in CH_2Cl_2.[40] In the cases of silyl enol ethers (Table 1, entries 5–10 and 12), the solutions become homogeneous after addition of the second aldehyde (R^2CHO), so insoluble Br–Bi=O does not accumulate. In addition, ligand exchange reactions involving the kinetically-labile Bi(III) center can produce reactive intermediates in acylation and other reactions.[36,37,38] Finally, Mukaiyama aldol reactions occur with addition of 100 mol % methyl di-*tert*-butylpyridine (DTBP) in the presence of 15 mol % of $BiBr_3$. Regardless of the explicit and potentially complex role(s) of $BiBr_3$, use of this salt in catalytic quantities is convenient and inexpensive.

In short, we have developed an efficient, diastereoselective one-pot, three component Mukaiyama aldol/addition/ISMS reaction to afford valuable 2,6-disubsituted dihydropyran products. Both ketene silyl acetals and silyl enol ethers are effective nucleophiles with β,γ-unsaturated aldehyde, **1**. Aliphatic, benzylic and aromatic aldehydes were all useful as the second electrophile (R^2CHO), although benzaldehyde provided the lowest yield. We are in the process of further optimizing reactions with aromatic aldehydes, establishing the role(s) of $BiBr_3$ in the reaction sequence as well as applying this methodology toward more substituted products.

3. Experimental section

3.1. General

All reagents were used as received unless otherwise noted. Dichloromethane was distilled from CaH_2 and THF was purified via a Solv-Tek® solvent purification system. Benzaldehyde, phthaldehyde, isobutyraldehyde as well as 2-ethylbutyraldehyde were purchased from Acros Organics. Dess-Martin periodininane, hexanal, octanal, bismuth bromide, methyl trimethylsilyl dimethylketene acetal, (2,2-dimethyl-1-methylenepropoxy)trimethylsilane, and 1-phenyl-1-trimethylsiloxyethylene were purchased from Aldrich Chemical Company. 4-Trimethylsilyl-3-butyn-1-ol was purchased from GFS Chemical. ^{13}C NMR spectra were recorded with the aid of an APT sequence in which methylene and quaternary carbons=even (e) and methyl and methine carbons=odd (o). Coupling constants were determined by the method of Hoye.[41] Thin layer chromatography was performed on Sorbent Technologies general-purpose silica gel on glass and flash chromatography was performed using Sorbent Technologies chromatographic silica gel (200–475 MESH). All compounds were judged to be homogeneous by ^{1}H and ^{13}C NMR spectroscopy.

3.2. General procedure

*3.2.1. Preparation of methyl cis-2-(6-benzyl-3,6-dihydro-2H-pyran-2-yl)-2,2–dimethyl propanoate (**3a**)*

$BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv) was weighed into 25 mL round bottom flask and 10 mL CH_2Cl_2 was added via syringe. (*Z*)-4-(trimethylsilyl)but-3-enal, **2**[5] (0.142 g, 1.00 mmol, 1.00 equiv) and methyl trimethylsilyl dimethylketene acetal (0.192 g, 1.10 mmol, 1.10 equiv) were added by syringe simultaneously. The mixture was stirred at room temperature until (*Z*)-4-(trimethylsilyl)but-3-enal, **2** was consumed by TLC (3 h). Additional $BiBr_3$ (45 mg, 0.010 mmol, 0.10 equiv) and phenylacetaldehyde (0.24 g, 2.0 mmol, 2.0 equiv) were added and the mixture was stirred for 12 h at rt. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.34) to provide 0.175 g (64%) of *cis*-isomer as a colorless oil: IR (neat) 3031 (s), 2982 (s), 2940 (s), 2879 (m), 1735 (s), 1451 (m), 1267 (s), 1140 (s), 1086 (s), 751 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.17–7.28 (m, 5H), 5.77–5.82 (m, 1H), 5.63 (dm, *J*=10.3 Hz, 1H), 4.27 (br, 1H), 3.77 (dd, *J*=11.0, 3.3 Hz, 1H), 3.55 (s, 3H), 2.83 (dd, *J*=13.9, 8.1 Hz, 1H), 2.70 (dd, *J*=13.9, 8.1 Hz, 1H), 2.06–2.15 (m, 1H), 1.77–1.85 (m, 1H), 1.21 (s, 3H), 1.20 (s, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 177.2 (e), 138.7 (e), 129.72 (o), 129.69 (o), 128.0 (o), 126.1 (o), 125.0 (o), 78.4 (o), 76.5 (o), 52.0 (o), 46.6 (e), 42.1 (e), 25.4 (e), 21.3 (o), 20.4 (o). Anal. Calcd for $C_{17}H_{22}O_3$ (274.35): C 74.42, H 8.08; found: C 74.53, H 8.30.

*3.2.2. Preparation of methyl cis-2-(6-isopropyl-3,6-dihydro-2H-pyran-2-yl)-2,2–dimethyl propanoate (**3b**)*

Using the general procedure, **3b** was prepared from $BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv), (*Z*)-4-(trimethylsilyl)but-3-enal **2** (0.142 g, 1.00 mmol, 1.00 equiv), methyl trimethylsilyl dimethylketene acetal (0.192 g, 1.10 mmol, 1.10 equiv), isobutyraldehyde (0.182 mL, 2.00 mmol, 2.00 equiv), and $BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv). The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.52) to provide 0.120 g (53%) of *cis*-isomer as a colorless oil: IR (neat) 2961 (s), 1737 (s), 1458 (w), 1368 (w), 1258 (m), 1136 (m), 1084 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.80–5.85 (m, 1H), 5.63 (dm, *J*=10.3 Hz, 1H), 3.86 (br, 1H), 3.75 (dd, *J*=10.6, 2.9 Hz, 1H), 3.67 (s, 3H), 2.04–2.12 (m, 1H), 1.76–1.83 (m, 1H), 1.70 (dtt, *J*=7.0, 7.0, 5.1 Hz, 1H), 1.22 (s, 3H), 1.14 (s, 3H), 0.90 (d, *J*=7.0 Hz, 3H), 0.86 (d, *J*=7.0 Hz, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 177.4 (e), 128.9 (o), 125.1 (o), 80.0 (o), 77.9 (o). 52.0 (o), 46.7 (e), 32.9 (o), 25.5 (e), 21.2 (o), 20.4 (o), 18.6 (o), 17.5 (o). Anal. Calcd for $C_{13}H_{22}O_3$ (226.31): C 68.99, H 9.80; found: C 68.29, H 9.61.

*3.2.3. Preparation of methyl cis-2-(6-pentyl-3,6-dihydro-2H-pyran-2-yl)-2,2-dimethyl propanoate (**3c**)*

This compound was prepared according to the general procedure described for **3a** using $BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv), (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.142 g, 1.00 mmol, 1.00 equiv), methyl trimethylsilyl dimethylketene acetal (0.192 g, 1.10 mmol, 1.10 equiv), hexanal (0.14 mL, 2.0 mmol, 2.0 equiv) and $BiBr_3$

(45 mg, 0.10 mmol, 0.10 equiv). The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.52) to provide 0.163 g (64%) of *cis*-isomer as a colorless oil: IR (neat) 3032 (m), 2953 (s), 2934 (s), 2861 (s), 1737 (s), 1469 (m), 1368 (w), 1265 (s), 1190 (m), 1134 (m), 1083 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74–5.80 (m, 1H), 5.59 (dm, J=10.3 Hz, 1H), 4.05 (br, 1H), 3.76 (dd, J=10.9, 2.3 Hz, 1H), 3.67 (s, 3H), 2.05–2.14 (m, 1H), 1.76–1.84 (m, 1H), 1.23–1.48 (m, 8H), 1.22 (s, 3H), 1.13 (s, 3H), 0.88 (t, J=7.0 Hz, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 177.4 (e), 130.8 (o), 124.3 (o), 78.2 (o), 75.5 (o), 52.0 (o), 46.6 (e), 35.5 (e), 32.0 (e), 25.5 (e), 25.1 (e), 23.0 (e), 21.1 (o), 20.5 (o), 14.4 (o). Anal. Calcd for $C_{15}H_{26}O_3$ (254.37): C 70.83, H 10.30; found: C 70.63, H 10.27.

3.2.4. Preparation of methyl cis-2-(6-(2-formylphenyl)-3,6-dihydro-2H-pyran-2-yl)-2,2-dimethyl-propanoate (**3d**)

This compound was prepared according to the general procedure using $BiBr_3$ (22 mg, 0.05 mmol, 0.10 equiv), (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.071 g, 0.50 mmol, 1.00 equiv), methyl trimethylsilyl dimethylketene acetal (0.096 g, 0.55 mmol, 1.10 equiv), phthalaldehyde (0.134 g, 1.00 mmol, 2.00 equiv), and additional $BiBr_3$ (22 mg, 0.05 mmol, 0.10 equiv). The product was purified by column chromatography (8:2 petroleum ether:Et_2O, R_f=0.22) to provide 0.079 g (55%) of *cis*-isomer as a colorless oil: IR (neat) 3743 (w), 2980 (w), 1733 (s), 1698 (s), 1558 (m), 1464 (m), 1266 (m), 1195 (m), 1139 (m), 1077 (m), 760 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 10.33 (s, 1H), 7.88 (dd, J=7.7, 1.1 Hz, 1H), 7.56–7.63 (m, 2H), 7.47 (td, J=7.3, 1.5 Hz, 1H), 5.90–5.95 (m, 1H), 5.85–5.88 (m, 1H), 5.78–5.82 (dm, J=10.3 Hz, 1H), 4.13 (dd, J=11.0, 3.3 Hz, 1H), 3.70 (s, 3H), 2.27–2.38 (m, 1H), 1.97–2.04 (dm, J=17.2 Hz, 1H), 1.29 (s, 3H), 1.22 (s, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 192.7 (o), 177.0 (e), 143.6 (e), 134.0 (o), 133.6 (e), 131.4 (o), 129.7 (o), 128.0 (o), 127.8 (o), 124.7 (o), 78.8 (o), 75.5 (o), 52.2 (o), 46.7 (e), 25.1 (e), 21.4 (o), 20.6 (o); HRMS (ESI) calcd for $C_{17}H_{20}O_4Na$ ($M+Na^+$) 311.1254, found 311.1251.

3.2.5. Preparation of cis-2-(6-pentyl-3,6-dihydro-2H-pyran-2-yl)-1-phenylethanone (**3e**)

$BiBr_3$ (22 mg, 0.05 mmol, 0.10 equiv) and NaI (23 mg, 0.15 mmol, 0.30 equiv) were weighed into 15 mL round bottom flask and 10 mL CH_2Cl_2 was added via syringe. After sonicating for 1 h at rt, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.071 g, 0.50 mmol, 1.00 equiv) and 1-phenyl-1-trimethylsilyloxyethylene (0.106 g, 0.55 mmol, 1.10 equiv) were added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2**, was consumed by TLC analysis (2 h). Hexanal (0.134 g, 1.00 mmol, 2.00 equiv) and additional $BiBr_3$ (22 mg, 0.05 mmol, 0.10 equiv) were added and the mixture was stirred for 12 h. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.38) to provide 0.104 g (76%) of *cis*-isomer as a colorless oil: IR (neat) 3743 (w), 2929 (s), 2861 (s), 1686 (s), 1452 (m), 1371 (m), 1336 (m), 1281 (m), 1217 (m), 1181 (m), 1075 (m), 993 (m), 751 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98–8.01 (m, 2H), 7.56 (tt, J=7.3, 1.5 Hz, 1H), 7.44–7.48 (m, 2H), 5.77–5.82 (m, 1H), 5.64 (dm, J=10.3 Hz, 1H), 4.16–4.23 (m, 1H), 4.08–4.14 (m, 1H), 3.40 (dd, J=15.7, 6.6 Hz, 1H), 2.98 (dd, J=15.7, 6.6 Hz, 1H), 2.02–2.18 (m, 2H), 1.18–1.50 (m, 8H), 0.85 (t, J=6.7 Hz, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 198.5 (e), 137.5 (e), 133.1 (o), 130.6 (o), 128.6 (o), 128.4 (o), 124.2 (o), 75.2 (o), 71.0 (o), 45.4 (e), 35.8 (e), 32.1 (e), 31.6 (e), 25.1 (e), 22.9 (e), 14.4 (o). Anal. Calcd for $C_{18}H_{24}O_2$ (272.38): C 79.37, H 8.88; found: C 79.22, H 9.01.

3.2.6. Preparation of cis-2-(6-(pentan-3-yl)-3,6-dihydro-2H-pyran-2-yl)-1-phenylethanone (**3f**)

$BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv) and NaI (50 mg, 0.15 mmol, 0.30 equiv) were weighed into 15 mL round bottom flask and 5 mL CH_2Cl_2 was added via syringe. After sonicating for 1 h at rt, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.142 g, 1.00 mmol, 1.00 equiv) and 1-phenyl-1-trimethylsiloxyethylene (0.212 g, 1.10 mmol, 1.10 equiv) were added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2**, was consumed (2 h). 2-Ethylbutyraldehyde (0.182 mL, 1.47 mmol, 1.47 equiv) and $BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv) were added and the mixture was stirred for 12 h. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.40) to provide 0.179 g (66%) of *cis*-isomer as a light yellow oil: IR (neat) 3032 (m), 2961 (s), 2932 (s), 2874 (s), 1684 (s), 1449 (m), 1279 (m), 1214 (m), 1184 (m), 1072 (s), 992 (m), 752 (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98–8.01 (dm, J=8.3 Hz, 2H), 7.56 (app. tm, J=7.3 Hz, 1H), 7.44–7.48 (m, 2H), 5.81–5.86 (m, 1H), 5.63 (dm, J=10.3 Hz, 1H), 4.12–4.19 (m, 2H), 3.36 (dd, J=15.7, 6.6 Hz, 1H), 2.94 (dd, J=15.7, 6.6 Hz, 1H), 2.01–2.16 (m, 2H), 1.16–1.40 (m, 5H), 0.84 (t, J=7.0 Hz, 3H), 0.83 (t, J=7.0 Hz, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 198.9 (e), 137.6 (e), 133.0 (o), 129.4 (o), 128.6 (o), 128.5 (o), 124.8 (o), 76.6 (o), 71.2 (o), 46.0 (o), 45.5 (e), 31.7 (e), 22.5 (e), 22.2 (e), 12.38 (o), 12.36 (o). Anal. Calcd for $C_{18}H_{24}O_2$ (272.38): C 79.37, H 8.88; found: C 79.71, H 8.96.

3.2.7. Preparation of cis-1-(6-heptyl-3,6-dihydro-2H-pyran-2-yl)-3,3-dimethylbutan-2-one (**3g**)

$BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv) and NaI (50 mg, 0.15 mmol, 0.30 equiv) were weighed into 15 mL round bottom flask and 5 mL CH_2Cl_2 was added via syringe. After sonicating for 1 h at rt, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.142 g, 1.00 mmol, 1.00 equiv) and (2,2-dimethyl-1-methylenepropoxy)trimethylsilane (0.190 g, 1.10 mmol, 1.10 equiv) were added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2** was consumed (2 h). Octanal (0.313 mL, 2.00 mmol, 2.00 equiv) and $BiBr_3$ (45 mg, 0.10 mmol, 0.10 equiv) were added and the mixture was stirred for 24 h. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was purified by column chromatography (9:1 petroleum ether:Et_2O, R_f=0.43) to provide 0.225 g (80%) of *cis*-isomer as a colorless oil: IR (neat) 3032 (m), 2957 (s), 2929 (s), 2858 (s), 1708 (s), 1465 (m), 1367 (m), 1185 (m), 1076 (s), 994 (m), 840 (w); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.63–5.68 (m, 1H), 5.51 (dm, J=10.3 Hz, 1H), 3.93–4.05 (m, 2H), 2.81 (dd, J=16.8, 7.0 Hz, 1H), 2.36 (dd, J=16.8, 7.0 Hz, 1H), 1.79–1.97 (m, 2H), 1.10–1.40 (m, 12H), 1.04 (s, 9H), 0.77 (t, J=6.7 Hz, 3H); ^{13}C NMR (APT) (100 MHz, $CDCl_3$) δ 213.8 (e), 130.6 (o), 124.2 (o), 75.2 (o), 70.7 (o), 44.6 (e), 43.3 (e), 35.9 (e), 32.1 (e), 31.3 (e), 29.9 (e), 29.6 (e), 26.4 (o), 25.5 (e), 23.0 (e), 14.5 (o). Anal. Calcd for $C_{18}H_{32}O_2$ (280.45): C 77.09, H 11.50; found: C 76.81, H 11.31.

3.2.8. Preparation of cis-3,3-dimethyl-1-(6-phenethyl-3,6-dihydro-2H-pyran-2-yl)butan-2-one (**3h**)

$BiBr_3$ (48 mg, 0.11 mmol, 0.10 equiv) was weighed into 15 mL round bottom flask and 5.0 mL CH_2Cl_2 was added via syringe. After stirring the $BiBr_3$ suspension for 5 min, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.152 g, 1.07 mmol, 1.00 equiv) and (2,2-dimethyl-1-methyleneпropoxy)trimethylsilane (0.206 g, 1.17 mmol, 1.09 equiv) were separately dissolved in 0.25 mL CH_2Cl_2 and added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2** was consumed by TLC analysis (2 h). $BiBr_3$ (51 mg, 0.11 mmol, 0.10 equiv) and 3-phenylpropanal (0.281 mL, 2.14 mmol, 2.00 equiv) and were then added and the mixture was stirred for 14 h. The solution was concentrated in vacuo, filtered through a small SiO_2 column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was purified by column

chromatography (95:5 to 9:1 petroleum ether:Et_2O, R_f=0.50 in 9:1 hexanes:EtOAc) to provide 0.158 g (52%) of the *cis*-isomer as a colorless oil: IR (neat) 3062 (m), 3027 (s), 2967 (vs), 2933 (m), 2869 (s), 1705 (vs), 1087 (vs), 1068 (vs); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26–7.32 (m, 2H), 7.16–7.21 (m, 3H), 5.81 (dddd, *J*=9.9, 7.3, 4.8, 2.2 Hz, 1H), 5.62 (dddd, *J*=10.3, 4.0, 2.7, 1.5 Hz, 1H), 4.09–4.15 (m, 2H), 2.97(dd, *J*=16.5, 7.3 Hz, 1H), 2.62–2.79 (m, 2H), 2.47 (dd, *J*=16.5, 5.1 Hz, 1H), 1.94–2.10 (m, 2H), 1.74–1.82 (m, 2H), 1.19 (s, 9H); ^{13}C (APT) (100 MHz, $CDCl_3$) δ 213.6 (e), 142.3 (e), 130.3 (o), 128.6 (o), 128.4 (o), 125.8 (o), 124.6 (o), 74.1 (o), 70.7 (o), 44.6 (e), 43.2 (e), 37.6 (e), 31.7 (e), 31.3 (e), 26.4 (o). Anal. Calcd for $C_{19}H_{26}O_2$ (286.41): C 79.68, H 9.15; found: C 79.64, H 9.18.

3.2.9. Preparation of methyl 2-methyl-2-(6-phenethyl-3,6-dihydro-2H-pyran-2-yl)propanoate (**3i**)

$BiBr_3$ (58 mg, 0.13 mmol, 0.10 equiv) was weighed into 15 mL round bottom flask and 5.0 mL CH_2Cl_2 was added via syringe. After stirring the $BiBr_3$ suspension for 5 min, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.180 g, 1.27 mmol, 1.00 equiv) and methyl trimethylsilyl dimethylketene acetal (0.295 g, 1.69 mmol, 1.33 equiv) were separately dissolved in 0.25 mL CH_2Cl_2 and added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2** was consumed by TLC analysis (1.5 h). $BiBr_3$ (58 mg, 0.13 mmol, 0.10 equiv) was then added followed by 3-phenylpropanal (0.340 mL, 2.52 mmol, 1.98 equiv) and the mixture was stirred for 14 h. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was finally purified by column chromatography (95:5 to 9:1 petroleum ether:Et_2O, R_f=0.48 in 9:1 hexanes:EtOAc) to provide 0.237 g (65%) of the *cis*-isomer as a colorless oil: IR (neat) 3028 (vs), 2980 (vs), 2874 (vs), 1728 (vs); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.24–7.29 (m, 2H), 7.14–7.20 (m, 3H) 5.80 (dddd, *J*=9.9, 4.2, 2.0, 2.0 Hz, 1H), 5.58 (dddd, *J*=9.9, 2.9, 1.5, 1.5 Hz, 1H), 4.08 (br s, 1H), 3.80 (dd, *J*=10.8, 3.1 Hz, 1H), 3.70 (s, 3H), 2.62–2.80 (m, 2H), 2.08–2.17 (m, 1H), 1.68–1.74 (m, 3H), 1.26 (s, 3H), 1.16 (s, 3H); ^{13}C (APT) (100 MHz, $CDCl_3$) δ 177.3 (e), 142.5 (e), 130.4 (o), 128.7 (o), 128.3 (o), 125.7 (o), 124.7 (o), 78.1 (o), 74.3 (o), 52.0 (o), 46.6 (e), 37.4 (e), 31.5 (e), 25.5 (e), 21.2 (o), 20.5 (o); Anal. Calcd for $C_{18}H_{24}O_3$ (286.41): C 74.97, H 8.39; found: C 74.92, H 8.44.

3.2.10. Preparation of 2-(6-phenyl-3,6-dihydro-2H-pyran-2-yl)-1-phenylethanone (**3j**)

$BiBr_3$ (48 mg, 0.11 mmol, 0.10 equiv) was weighed into 15 mL round bottom flask and 3.5 mL CH_2Cl_2 was added via syringe. After stirring the $BiBr_3$ suspension for 5 min, (*Z*)-4-(trimethylsilyl)but-3-enal, **2** (0.153 g, 1.07 mmol, 1.00 equiv) and 1-phenyl-1-trimethylsiloxyethylene (0.237 g, 1.23 mmol, 1.15 equiv) were dissolved separately in 0.25 mL CH_2Cl_2 and added by syringe simultaneously. The mixture was stirred until (*Z*)-4-(trimethylsilyl)but-3-enal, **2** was consumed by TLC analysis (1.5 h). $BiBr_3$ (50 mg, 0.11 mmol, 0.10 equiv) and benzaldehyde (0.218 mL, 2.15 mmol, 2.01 equiv) were then added and the mixture was stirred for 4 h. The solution was concentrated in vacuo, filtered through a small SiO_2 pipette column with CH_2Cl_2 as eluent and concentrated in vacuo again. The product was finally purified by column chromatography (95:5 to 9:1 petroleum ether:Et_2O, R_f=0.16 with 9:1 petroleum ether:Et_2O) to provide 0.131 g (44%) of the *cis*-isomer as a light yellow oil: IR (film) 3062 (m), 3033 (m), 2922 (m), 1683 (vs), 1598 (vs), 1450 (vs); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (dm, *J*=8.1 Hz, 2H), 7.52–7.58 (m, 1H), 7.42–7.48 (m, 2H), 7.32–7.38 (m, 4H), 7.24–7.30 (m, 1H), 5.91–5.97 (m, 1H), 5.77 (dm, *J*=10.3 Hz, 1H), 5.24 (br s, 1H), 4.46 (dddd, *J*=9.9, 6.2, 4.0, 4.0 Hz, 1H), 3.47 (dd, *J*=16.5, 6.2 Hz, 1H), 3.10 (ddd, *J*=16.5, 6.2, 0.7 Hz, 1H), 2.15–2.33 (m, 2H); ^{13}C (APT) (100 MHz, $CDCl_3$) δ 198.0 (e), 141.4 (e), 137.3 (e), 133.2 (o), 130.0 (o), 128.7 (o), 128.6 (o), 128.4 (o), 127.9 (o), 127.3 (o), 124.6 (o), 77.9 (o), 71.0 (o), 45.3 (e), 31.1 (e); HRMS (ESI) calcd for $C_{19}H_{18}O_2Na$ ($M+Na^+$) 301.1199, found 301.1195.

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Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2009.06.083.

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