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Electric-Field Triggered Controlled Release of Bioactive Volatiles from Imine-Based Liquid Crystalline Phases

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Abstract: Application of an electric field to liquid crystalline film forming imines with negative dielectric anisotropy, such as *N*-(4-methoxybenzylidene)-4-butylaniline (MBBA, **1**), results in the expulsion of compounds that do not participate in the formation of the liquid crystalline phase. Furthermore, amines and aromatic aldehydes undergo component exchange with the imine by generating constitutional dynamic libraries. The strength of the electric field and the duration of its application to the liquid crystalline film influence the release rate of the expelled compounds and, at the same time, modulate the equilibration of the dynamic libraries. The controlled release of volatile organic molecules with different chemical functionalities from the film was quantified by dynamic headspace analysis. In all cases, higher headspace concentrations were detected in the presence of an electric field. These results point to the possibility of using imine-based liquid crystalline films to build devices for the controlled release of a broad variety of bioactive volatiles as a direct response to an external electric signal.

Keywords: controlled release · dynamic combinatorial chemistry · electric fields · imines · liquid crystals

Introduction

As a consequence of their well-organised structures, liquid crystals have found numerous applications in display technology, optical data storage, non-linear optics, high-performing polymers, and as delivery vehicles for bioactive matter.[1,2] Depending on the molecular structure and composition of the liquid crystalline phase forming materials, they can exist in various phases that are used as particles, gels, capsules or waxes for the encapsulation of active substances into the (lamellar or cubic) liquid crystalline phase. Liquid crystalline systems, especially those in polymeric forms, have served for the slow release of drugs in pharmaceutical applications,[3] but also for the release of flavours and fragrances in foods or cosmetics.[4,5] In most cases, a diffusion-controlled release of the active compound from the liquid crystalline phases was reported.

Due to rapid evaporation on exposure to air, the perception of volatile bioactive compounds is quite limited in time. As the performance of a perfumed or flavoured consumer article is dependent on the concentration of the respective compound in the air at a given time, the development of delivery systems for the controlled release of volatiles has become a major area of research in life sciences. Besides delivery systems that release compounds slowly over time,[6,7] there is considerable interest in the development of delivery systems that can rapidly release active substances using an external trigger, thus allowing their use as olfactive stimuli-response materials in air-freshening, insect attractant/repellent or signalling devices. A rapid response to the external trigger is thus a prerequisite for a well-performing delivery system of this type. Due to their polarity and/or chemical nature, only a restricted selection of active materials can be successfully released from individual capsules or conjugates.[6,7] Electric triggers are generally less sensitive towards the polarity and chemical functionality of bioactive molecules, and are therefore of interest in the release of a broad variety of compounds from a suitably designed device. The use of electric fields to release molecules, by inducing a phase change of polymeric liquid crystalline compounds, has

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been investigated for polypeptides.[8] Furthermore, it was recently reported that layer-by-layer assembled thin films release encapsulated compounds by destabilisation of the assembled structure under the effect of an electric field.[9] The films reacted to small electrochemical potentials and were found to re-stabilise once the applied potential was removed. However, the layer-by-layer directed self-assembly requires the incorporated material to possess well-defined complementary functionalities.

During our investigations on dynamic combinatorial chemistry (DCC) using reversible covalent reactions to set-up constitutional dynamic libraries (CDLs),[10] we became interested in developing adaptive chemical systems that can be modulated by component exchange as a result of external physical parameters (as for example phase transitions[11] or temperature changes[12]), or by chemical triggers (such as variations in pH[12,13] or the presence of metal ions[13,14]). Furthermore, in this context, we recently reported that electric fields influence the equilibrium mixtures of constitutionally related and interconvertible compounds.[15] Application of an electric field to liquid crystalline type imines with a negative dielectric anisotropy, such as *N*-(4-methoxybenzylidene)-4-butylaniline (MBBA, **1**) or its ethoxy analogue, resulted in the observation that compounds that do not participate in the formation of the nematic phase, as for example cyclopentanol, are expelled from the liquid crystal in the presence of an electric field. Compounds that can react with the liquid crystalline phase forming imines undergo component exchange at the isotropic and nematic phase transition, as illustrated in Scheme 1a for the reaction between **1** and cyclopentylamine.[15]

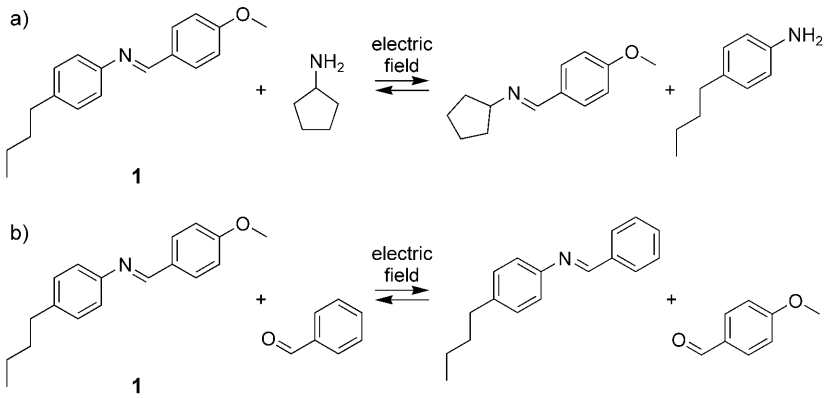
Based on the promising results obtained for the pH-dependent controlled release of volatiles from dynamic mixtures comprising hydrazones,[16] we now investigated the potential of releasing volatiles from liquid crystalline phase-forming imines triggered by an electric field. In a first step we studied the expulsion of compounds that do not participate in the liquid crystalline phase formation (alcohols, esters, lactones or nitriles), in a second step we investigated the possibility of component exchange for the controlled release of amines (Scheme 1a) or carbonyl compounds (Scheme 1b).

Results and Discussion

Electric field-dependent expulsion of compounds that do not participate in the liquid crystalline phase formation: To demonstrate the expulsion of volatile compounds during the formation of the liquid crystalline phase under the influence of an electric field, a homogenised mixture of liquid crystalline phase-forming imine **1** and cyclopentanol (44 mol%) was placed as a film between two commercially available indium tin oxide (ITO) coated glass plates (7.25×2.5 cm). To apply high enough voltages while keeping the resistivity below $6\times10^7\,\Omega\,cm^{-1}$ (to avoid decomposition of the compounds by the electric current) ideally the film has to be very thin.[15] A film of about 21 μm (±5%) thickness was obtained by pipetting 38 μL of the alcohol/imine mixture onto one of the ITO plates and by slightly pressing another slide on top of it in such a way to cover most of the surface between the two glass plates with the film (ca. 17.5 cm^2). The glass plates were each connected at one end to either one of the poles of a benchtop power supply, which was adjusted to generate a tension between 0 and 75 V. The film was then exposed to a constant voltage (75 V, corresponding to $3.6\times10^4\,V\,cm^{-1}$). Due to the opacity of the nematic phase formed upon application of the voltage, the isotropic/nematic phase transition could be observed with the naked eye.[15] After eight hours the experiment was stopped, and the film was rinsed off the plates with $CDCl_3$. ^1H NMR spectroscopy revealed that the amount of remaining cyclopentanol in the film was 8.5 mol%. If no electric field was applied, the remaining amount of cyclopentanol was found to be 37 mol%. When keeping the mixture in a closed vial no change in the composition was observed after two hours.

That the loss of cyclopentanol observed in the presence of the electric field was not the result of a variation in temperature was verified by heating the ITO plates in the absence of the field. Heating, even by tens of degrees, resulted in a much smaller loss of cyclopentanol than was observed with the electric field.[15] NMR analysis showed that the composition of a solution of **1** and cyclopentanol in $CDCl_3$, which was kept between 22.5 and 30°C for 2 h, remained unchanged. Similarly, the application of pressure (7 $kg\,cm^2$) to a film of **1** and cyclopentylamine (4:1) had no influence on the composition of the mixture.[17]

To follow the evaporation of the volatile compounds in the presence of the electric field, we investigated the expulsion



Scheme 1. Principle of constitutional reorganisation by component exchange of MBBA (**1**) with cyclopentylamine (a) or benzaldehyde (b) in the presence of an electric field.

of the compounds from the liquid crystalline phase as a function of the applied voltage by dynamic headspace analysis.[18] For practical reasons (especially to avoid displacement of the glass plates while positioning them inside the headspace cell) and to increase the amount of compounds to be placed between the glass slides, two Teflon strips were used as spacers to ensure a constant distance between the slides. The thickness of the resulting liquid crystalline film was thus increased to about 0.1 mm, which allowed the deposition of 100 μL of the mixture.

For the measurements, cyclopentanol was added to MBBA (**1**), and the mixture was placed between the coated sides of two ITO glass slides. The slides were pressed together to form a uniform and transparent film covering almost the entire surface between the slides, before being fixed on a glass support. The total set-up was then placed inside a homemade headspace sampling cell (Figure 1) and connected to the two poles of a benchtop power supply. A constant flow of air (ca. 206 mL min^{-1}) was aspirated through a filter of activated carbon, a saturated solution of NaCl (to ensure a constant air humidity of ca. 75 %),[19] and then through the headspace cell. The expelled volatiles were trapped at constant time intervals on Tenax cartridges. During the entire measurement, the voltage on the power supply was fixed at either 60 or 75 V, resulting in an electric field of 6000 and 7500 V cm^{-1}, respectively. As a control experiment carried out in parallel, no tension was applied to the slides. Twelve samples were taken altogether, and the cartridges were thermally desorbed and analysed by GC. Headspace concentrations of cyclopentanol (in ng per litre of air) were determined by external standard calibration.

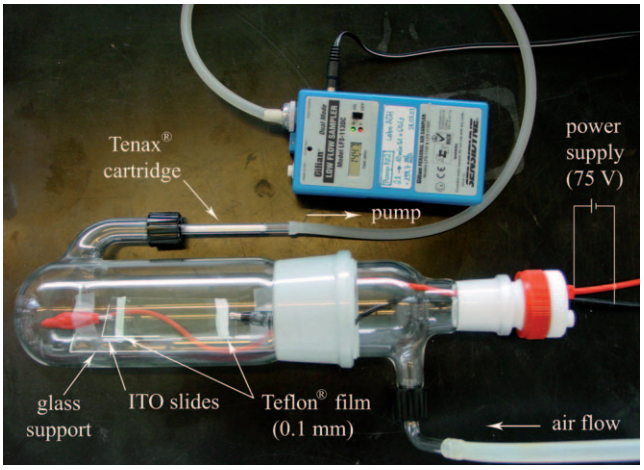


Figure 1. Set-up of the headspace sampling cell (inner cell volume ca. 625 mL).

All experiments were carried out in triplicate. The average headspace concentrations measured for the release of cyclopentanol from the liquid crystalline film are illustrated in Figure 2; the absolute headspace concentration obtained for all measurements are listed in the Supporting Information.

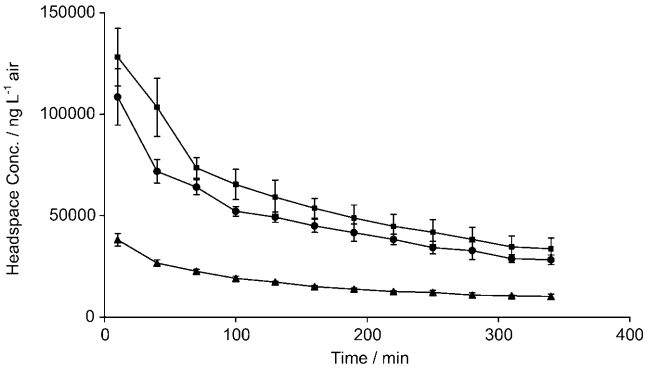


Figure 2. Comparison of the average headspace concentrations measured for the evaporation of cyclopentanol from a liquid crystalline film of **1** after application of 0 V (▲), 60 V (●) and 75 V (■).

The liquid crystalline film between the two glass slides remained transparent during the measurement, but turned to a slightly brownish-yellow colour. Small opaque areas, corresponding to the formation of the nematic phase, were formed along the outer borders of the ITO slides. At the end of the headspace sampling, the film was dissolved with $CDCl_3$, analysed by NMR spectroscopy and compared to the original mixture from the start of the experiment. The original mixture contained 70 mol % of cyclopentanol, whose amount at the end of the measurement was determined to be 41, 33 and 22 mol % after being exposed to a voltage of 0, 60 and 75 V for 375 min (6.25 h), respectively. The data (before and after the measurement) show that with increasing voltage of the applied electric field an increasing amount of cyclopentanol was evaporated from the film. The film of the reference sample (where no voltage was applied) remained transparent and did not change its original colour (slightly yellow).

No evidence for the formation of degradation products was observed in the NMR spectra. Nevertheless, it is interesting to note that an arboresque-like, insoluble brownish film of unknown composition remained at the ITO surface which was connected to the anode.

The headspace data show that the experiment is quite reproducible, and similar results were obtained by using either new or previously used ITO glass plates. Even the insoluble brownish film seems to have no influence on the experiment (the slides were re-used in the following experiments).

In similar experiments, mixtures of terpene alcohols (+)-(*R*)-citronellol (**2**), (−)-(1*R*,2*S*,5*R*)-menthol (**3**) and (±)-linalool (**4**) or benzyl acetate (**5**), (±)-4-octanolide (**6**), and (±)-2-methyldecanenitrile (**7**) were added to **1**, respectively. The homogenised clear solutions were deposited as thin films between two ITO-coated glass slides and analysed after application of a voltage of 0 (reference) and 75 V as described above. The data obtained for the release of terpene alcohols **2**–**4** are shown in Figure 3; those for the ester, lactone and nitrile **5**–**7** are depicted in Figure 4.

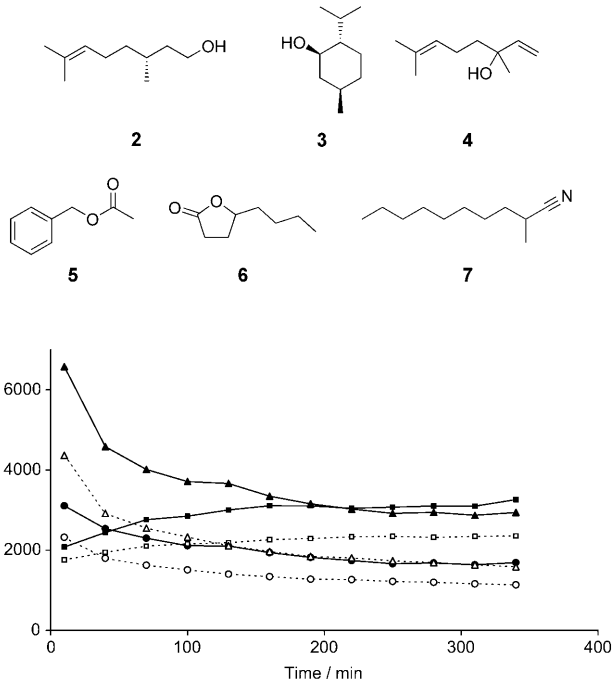


Figure 3. Comparison of the average headspace concentrations measured for the evaporation of alcohols **2** (■, □), **3** (●, ○) and **4** (▲, △) from a liquid crystalline film of **1** in the presence (solid line) or absence (dotted line) of an applied electric field.

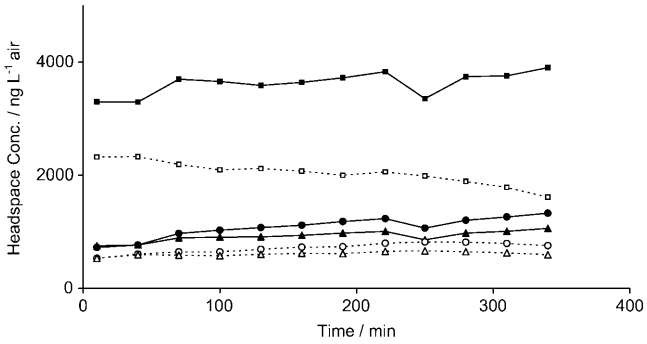


Figure 4. Comparison of the average headspace concentrations measured for the evaporation of compounds **5** (■, □), **6** (●, ○) and **7** (▲, △) from a liquid crystalline film of **1** in the presence (solid line) or absence (dotted line) of an applied electric field.

The headspace data recorded for the release of **2–7** generally showed larger standard deviations than in the previous experiment with cyclopentanol (see the Supporting Information). In the case of **2**, this may be due to the fact that the response of the compound at the FID-detector of the GC is relatively small, resulting in smaller peak areas. Furthermore, in one of the experiments with the terpene alcohols, the film between the two glass plates was less regularly spread, thus causing possible slight variations in the film thickness. Nevertheless, the data were found to be reproducible and, in all cases, the presence of the electric field increased the amounts of volatiles released from the system.

Analysis of the ^{1}H NMR data before and after the experiment (performed only once for each series) confirmed the trend observed from the headspace measurements. However, due to a considerable peak overlap and the small amounts of volatiles relative to butylaniline derivative **1**, the ^{1}H NMR integration data were found to be less precise than the headspace measurements.

The formation of the brownish film on the slide connected to the anode of the power supply (see above) was found to be significantly less pronounced in the experiments with compounds **2–7**, as compared to the previous experiments with cyclopentanol.

Besides the voltage of the applied electric field, the amount of volatiles released during the experiment depends on the vapour pressure (volatility) of the respective compounds. The calculated vapour pressures of 2.25 (**2**), 2.58 (**3**), 3.54 (**7**), 3.96 (**6**), 11.09 (**4**) and 24.93 Pa (**5**)[20] roughly account for the measured headspace concentrations of the different compounds, with the highest concentrations of each series corresponding to the most volatile compound (linalool (**4**), and benzyl acetate (**5**)), and the lowest concentrations for the least volatile compounds (citronellol (**2**) and 2-methyldecanenitrile (**7**)).

The measurements show that a voltage-dependent release of bioactive volatiles by expulsion from the liquid crystalline film is possible, even if compound mixtures are used. Furthermore, with the human olfactory thresholds of fragrances **2–5** being at 46, 269, 347 and 912 ng L^{-1}, respectively,[21] the measured headspace concentrations all lie far above this threshold value, and the compounds can thus easily be detected by humans for the entire duration of the experiment.

Electric field-dependent expulsion of compounds undergoing component exchange with the liquid crystalline phase-forming imine: If compounds that react reversibly with the liquid crystalline phase-forming imine were added (such as primary and secondary amines), component exchange by transamination was observed.[15] The composition of the final mixture was thereby influenced by the presence or absence of an electric field. For example, a mixture of MBBA (**1**) with cyclopentylamine (64 mol%) gave, after equilibration in a closed vial for 20 h, a mixture containing only 33 mol% of **1**. A content of 38 mol% of **1** was obtained when the mixture was placed between the ITO glass plates without applying an electric field. However, the presence of an electric field (3.1×10^4 V cm^{-1}) shifted the equilibrium to 69 mol% of **1** in the final composition. Similarly, a 2:1 mixture of **1** and benzylamine gave an equilibrium containing only 6 mol% of **1** after 20 h in a closed vial, 8 mol% when placed between the ITO plates, but 25 mol% when the electric field was applied for the same period of time. In both cases the formation of the liquid crystalline film forming imine **1** was favoured in the presence of the electric field.

Replacing the liquid crystal by pentaethyleneglycol (having the same viscosity as **1**) and applying the electric field (3.0×10^4 V cm^{-1}) on a mixture with cyclopentylamine for 4 h showed that exactly the same amount of cyclopentylamine was evaporated in the presence or absence of the

electric field, and that the expulsion of the compound is in fact the result of the applied electric field to the liquid crystalline phase.

This was also observed when an equimolar mixture of amines **8**-**11** (each at 25 mol% with respect to **1**) was equilibrated with imine **1**. Transamination gave rise to four additional imines **12**–**15**, which were quantified by ^{1}H NMR spectroscopy (in $CDCl_3$) after 18 h of equilibration in a closed vial, as a film between two ITO glass slides (without application of an electric field) and between two glass slides in the presence of an electric field (3.0×10^4 V cm^{-1}), respectively. The composition of the equilibrated mixtures is given in Table 1.

8 **9** **10** **11**

1: R = 4-butylphenyl
12: R = allyl
13: R = 3-methylbutyl
14: R = cyclopentyl
15: R = benzyl

Table 1. Composition of an equilibrated mixture of imine **1** with amines **8**–**11** determined by ^{1}H NMR spectroscopy.

Compound	Composition [mol%] after 18 h of equilibration in a closed vial	between ITO plates without electric field	between ITO plates with electric field (3×10^4 V cm^{-1})
1	27.7	34.3	49.9
12	13.6	8.8	5.5
13	20.6	17.8	7.7
14	16.2	17.0	15.6
15	21.9	22.1	21.3

Depending on the equilibration conditions, mixtures with a variable content of imines **12**–**15** were obtained. In the presence of the electric field the amount of **1** in the equilibrated mixture remained at 50 mol%, whereas in the absence of the field it dropped to a value below 35 mol%. The electric field favours the formation of a liquid crystalline film of **1**, and the resulting electro-rheological effect expels the amines which do not participate in the formation of the liquid crystalline film. Interestingly, the amounts of **14** (ca. 16 mol%) and **15** (ca. 22 mol%) remained constant in all three samples, which is presumably due to the fact that the corresponding amines **10** and **11** are the least volatile amines of the series, with vapour pressures of 26.5 and 0.8 Pa, respectively. The more volatile analogues **8** and **9** (257.0 and 44.5 Pa) are expelled first, which decreases the amount of imines **12** and **13** in the mixture in favour of the liquid crystalline phase-forming imine **1**.

Because amines are less interesting as bioactive compounds to be released, we were interested to see whether an exchange and release of the aldehyde part of the imine was also possible. The reversible formation of imines requires the presence of at least trace amounts of water, which could be present either in the film or result from ambient humidity. We thus investigated the effect of the electric field on the evaporation of a series of aromatic aldehydes and ketones to be exchanged with **1**, by dynamic headspace analysis, as described above. Benzaldehyde (**16**), 4-ethylbenzaldehyde (**17**) and acetophenone (**18**) were chosen as the volatiles to be released. If the carbonyl compounds react with the imine

16 **17** **18** **19**

1: R^1 = OCH_3 R^2 = H
20: R^1 = H R^2 = H
21: R^1 = CH_2CH_3 R^2 = H
22: R^1 = H R^2 = CH_3

by component exchange, 4-methoxybenzaldehyde (**19**) is expected to be generated and released into the headspace by expulsion from the liquid crystalline phase-forming imine. ^{1}H and ^{13}C NMR spectroscopy, as well as GC/MS analysis of the film after the analysis, combined with a comparison of GC retention times of the headspace samples, confirmed the formation of **19**, both in the presence and absence of the electric field. Furthermore, the generation of *N*-(benzylidene)-4-butylaniline (**20**) and *N*-(4-ethylbenzylidene)-4-butylaniline (**21**) was demonstrated, whereas the formation of the corresponding ketone derivative of acetophenone **22** was not observed. The identity of imines **20** and **21** was confirmed by synthesis of the reference compounds[22] and comparison of their spectroscopic data. The headspace data measured in the presence and absence of the electric field (average of two measurements) are illustrated in Figure 5.

In a similar experiment, **16**, **18** and **19** were mixed together and added to *N*-(4-ethylbenzylidene)-4-butylaniline (**21**). The film of the compound mixture was then exposed to a

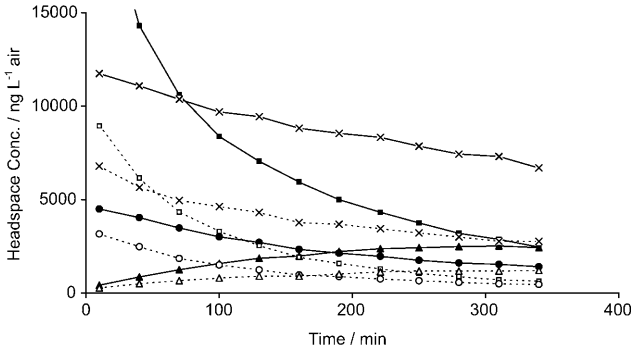


Figure 5. Comparison of the average headspace concentrations measured for the evaporation of carbonyl compounds **16** (■, □), **17** (●, ○), **18** (×) and **19** (▲, △) from a liquid crystalline film of **1** in the presence (solid line) or absence (dotted line) of an applied electric field.

voltage of 75 V or 0 V (reference) as described above. Again, the headspace concentrations of **16**, **18**, and **19** continuously decreased during the experiment and an increasing amount of 4-ethylbenzaldehyde (**17**) was formed over time by component exchange (Figure 6), thus illustrating the general nature of the principle. In all cases, the presence of the electric field afforded higher headspace concentrations than the reference sample without an electric field, and the headspace concentrations still correlated with the vapour pressures of the volatiles (**16**: 134.6 Pa, **18**: 43.5 Pa, **17**: 16.6 Pa and **19**: 4.0 Pa).[20]

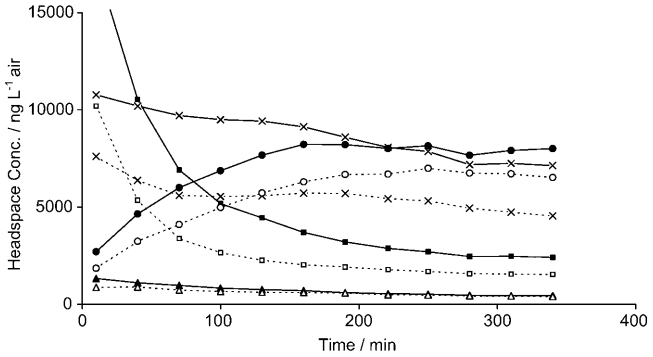


Figure 6. Comparison of the average headspace concentrations measured for the evaporation of carbonyl compounds **16** (■, □), **17** (●, ○), **18** (×) and **19** (▲, △) from a liquid crystalline film of **21** in the presence (solid line) or absence (dotted line) of an applied electric field (single measurement).

^{1}H NMR analysis of the film before and after the experiment correlated with the headspace data, with the exception of acetophenone, where a higher concentration was measured after the headspace sampling. As the component exchange also takes place in the absence of the electric field, it should be noted that no absolute values corresponding to the mixture at the beginning of the measurement could be obtained by NMR spectroscopy, as component exchange in the NMR tube could not be excluded.

With the human olfactory thresholds of **16** and **18** being at 186 and 1820 ng L^{-1}, respectively,[21] the measured headspace concentrations lie far above these threshold values, and the compounds can thus easily be detected by humans for the entire duration of the experiment.

Conclusions

Application of an electric field to liquid crystalline film-forming imines with negative dielectric anisotropy results in the expulsion of compounds that do not participate in the formation of the liquid crystalline phase. If these compounds can reversibly react with the imine by component exchange, the field influences the equilibrium state of constitutional dynamic mixtures of imines. Both amines and aldehydes are exchanged upon formation of a CDL of the corresponding imines,[23] and volatile compounds are more readily expelled from the liquid crystalline film than non-volatiles. Liquid crystalline forming imines are therefore suitable materials to modulate controlled release of volatile organic compounds by application of an electric field and point to the possibility of constructing electric devices that allow fine-tuning of the release rates of individual compounds and compound mixtures as a direct response to an electric signal.

In "classical" delivery systems, the release rates of the active compounds are defined by structural aspects that define the diffusion rates of the compounds from an encapsulating matrix or capsule[6] or the kinetics of a given covalent bond cleavage,[7] as well as by external parameters such as temperature or pH. The use of an electric field as the trigger allows the design of delivery systems that are independent of the chemical functionalities of the compounds to be released. Other parameters, such as a change in temperature, were found to present much weaker effects than the application of an electric field. The strength of the electric field and the duration of its application directly modulate the release of the active compounds as a function of their vapour pressures. Such a feature is of major interest for the efficient release of a broad variety of biologically active compounds in the area of life sciences.[24]

Experimental Section

General: If not stated otherwise, commercially available reagents and solvents were used without further purification. Reactions were carried out in standard glassware under N_2, and yields were not optimised. ITO coated glass slides were purchased from Aldrich (ca. 7.0×2.5 cm, 70–100 ohm resistance, ref. 576352). Electric fields were generated with a Thurlby Thandar Instruments (TTi) EX752M 75 V/150 V multimode benchtop power supply, operated between 0 and 75 V. UV/Vis spectra were recorded on a Perkin–Elmer Lambda 14 spectrometer, λ in nm (ε), IR spectra on a Spectrum One FTIR spectrometer, $\tilde{\nu}$ in cm^{-1}. ^{1}H and ^{13}C NMR spectra were recorded at 25 °C on a Bruker 400 MHz DPX or Avance spectrometer, δ in ppm downfield from Me_4Si as internal standard, J in Hz. GC-MS (EI) measurements were performed on a Hewlett Packard HP 5890 or 6890 GC System equipped with a Supelco SPB-1 capillary column (30 m, 0.25 mm i.d.) at 70 °C for 10 min then to 260 °C (10 °C min^{-1}), helium flow about 1 mL min^{-1}, coupled to a HP MSD 5972 or 5973 quadrupole mass spectrometer, electron energy about 70 eV, fragment ions m/z (rel. int. in % of the base peak).

Standard compound expulsion and crossover experiments: In a typical protocol the compounds were mixed in a closed vial, the mixture was heated up to 60 °C for 5 min, then cooled to room temperature and left for 2 h. A total of 38 μL (±5%) of the neat mixture was then placed between the coated sides of two ITO glass slides using a microsyringe. The slides were gently pressed together to obtain a thin film (21 μm, ±5%) covering the entire surface (ca. 18.1 cm^2). The slides were then thermostatted and connected to the different poles of the power supply. The electric field was applied with values between 0 and 75 V (for an applied field of 75 V, the experimental error led to a value of 3.5×10^4 V cm^{-1} ($\pm0.15\times10^4$ V cm^{-1}, ±5%). After a given time, the electric field was shut off, and the mixture between the two ITO slides dissolved in $CDCl_3$ (2 mL). ^{1}H NMR measurements were carried out within 5 min after dissolution of the film. For experiments with both fields and the thermostatted control experiment (without field and set up using the same initial mixture), ^{1}H NMR spectra were recorded until stabilisation of the equilibria. The values for the changes in sample composition were obtained

from comparison of the spectra for the two corresponding experiments after the same time of equilibration in solution.

Headspace measurements: The liquid crystalline phase mixture was prepared by adding 20 μL of the volatiles to 200 μL of **1**. A total of 100 μL of the homogenised mixture was then placed onto the coated side of an ITO-coated glass slide. To keep a constant distance between the two slides, a Teflon film (0.1 mm thickness) was placed at each end of the glass slide. The ITO glass slide was then covered with a second slide in such a way that the coated side was in contact with the solution, and that the slides were not completely superimposed on their smaller side (so as to fix a crocodile clamp on opposite sides of each glass slide). The slides were then pressed together to form a uniform and transparent film covering almost the whole surface between the slides. The set-up was taped to a glass support and placed inside a home-made headspace sampling cell (average volume ca. 625 mL) with the cables to the power supply passing through a Teflon stopper at the top of the cell, allowing a gas-tight fixing of the cables to the power supply. During the measurements, a constant flow of air was aspirated through a set-up composed of a filter of activated carbon (Norit RB 1 0.6, pellets), a wash bottle containing a saturated solution of NaCl (humidity of the air ca. 75%),[19] a second, empty wash bottle, the headspace cell, and a Tenax cartridge containing 100 mg of Tenax-TA (Varian). For the headspace sampling, a Gilian dual mode low flow sampler pump was used, which was calibrated at a flow rate of about 206 mL min^{-1}. All measurements were carried out in triplicate, if not stated otherwise, with the voltage on the power supply fixed at 60 or 75 V, respectively. The measurements were started by switching on the pump and, after 1 min, the voltage. No current was measured on the power supply during the experiment. The system was equilibrated for 10 min while sampling on a waste Tenax cartridge. After 10 min, the waste cartridge was replaced with a clean one, and the volatiles were trapped for 1 (cyclopentanol) or 2 min (all other compounds) onto a clean cartridge. Then the waste cartridge was replaced. In each case a control experiment was carried out in parallel under the same conditions, without however applying any voltage to the ITO plates. Altogether 12 samples were taken. In the experiment with cyclopentanol, the sampling was repeated every 29 min during 1 min, in all other experiments the sampling was repeated every 28 min during 2 min. The cartridges were thermally desorbed on a Perkin–Elmer TurboMatrix ATD desorber and analysed on a Carlo Erba MFC 500 gas chromatograph equipped with a I&W Scientific DB1 capillary column (30 m, i.d. 0.45 mm, film 0.42 μm) and FID detector. The volatiles were analysed using a two-step temperature gradient starting from 70 °C to 130 °C at 3 °C min^{-1} and then rising to 260 °C at 25 °C min^{-1}. The detector temperature was at 260 °C. Headspace concentrations (in ng per litre of air) were determined by external standard calibration. The calibrations were effected by using acetone solutions at eight different concentrations; 0.4 μL of each calibration solution were injected onto a clean Tenax cartridge. All the cartridges were desorbed immediately with increasing concentration under the same conditions as those resulting from the headspace sampling. Plotting the concentrations (in ng L^{-1}) against the peak areas gave straight lines with a correlation coefficient of $r^2 > 0.992$.

Synthesis of 4-butyl-*N*-[(1*E*)-phenylmethylene]aniline (20): A solution of 4-butylaniline (2.0 g, 13.4 mmol) and benzaldehyde (**16**, techn., containing benzoic acid, 1.42 g, 13.4 mmol) in ethanol (150 mL) was heated under reflux for 42–44 h. Then more **16** (0.71 g, 6.7 mmol) was added and the mixture was left stirring under reflux overnight. After cooling to room temperature, the reaction mixture was concentrated and the remaining volatiles were removed by bulb-to-bulb distillation to give a brownish oil (3.47 g (quant.)). ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.47$ (s, 1H), 7.92–7.85 (m, 2H), 7.49–7.42 (m, 3H), 7.23–7.12 (m, 4H), 2.63 (t, $J = 7.9$ Hz, 2H), 1.67-1.56 (m, 2H), 1.43–1.31 (m, 2H), 0.94 ppm (t, $J = 7.4$ Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 159.56$ (d), 149.61 (s), 140.89 (s), 136.39 (s), 131.17 (d), 129.11 (d), 128.72 (d), 128.71 (d), 120.80 (d), 35.19 (t), 33.70 (t), 22.35 (t), 13.98 ppm (q); IR (neat): $\tilde{\nu} = 3060$ w, 3024 w, 2997 w, 2955 m, 2926 m, 2870 m, 2855 m, 2731 w, 1958 w, 1897 w, 1813 w, 1759 w, 1704 w, 1627 m, 1598 m, 1577 m, 1504 m, 1464 m, 1450 m, 1416 w, 1377 w, 1365 w, 1331 w, 1311 m, 1296 w, 1236 w, 1191 m, 1168 m, 1113 m, 1071 m, 1024 w, 1015 w, 1000 w, 986 w, 971 m 927 w, 916 w, 882 m, 781 w, 754 s, 727 m, 689 s, 667 w, 652 w, 638 m, 626 w cm^{-1}; UV/Vis (ethanol): λ (ε) = 324 (11700), 264 (18000), 241 (12400), 232 (sh, 13100), 224 nm (14900); MS (EI): m/z (%): 238 ($[M+1]^+$, 7), 237 ($[M]^+$, 37), 195 (16), 194 (100), 193 (3), 91 (3), 90 (6), 89 (6), 77 (3).

Synthesis of 4-butyl-*N*-[(1*E*)-(4-ethylphenyl)methylene]aniline (21): As described for **20** with 4-ethylbenzaldehyde (**17**, 1.74 g, 13.0 mmol and 0.35 g, 2.6 mmol) to give a brownish oil (3.92 g (quant.)). ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.44$ (s, 1H), 7.81 (d, $J = 7.6$ Hz, 2H), 7.29 (d, $J = 8.2$ Hz, 2H), 7.22–7.10 (m, 4H), 2.71 (q, $J = 7.5$ Hz, 2H), 2.62 (t, $J = 7.7$ Hz, 2H), 1.67–1.56 (m, 2H), 1.37 (hex., $J = 7.5$ Hz, 2H), 1.27 (t, $J = 7.4$ Hz, 3H), 0.94 ppm (t, $J = 7.4$ Hz, 3H); ^{13}C NMR (100.6 MHz, $CDCl_3$): $\delta = 159.59$ (d), 149.83 (s), 147.93 (d), 140.66 (s), 134.06 (s), 129.08 (d), 128.81 (d), 128.30 (d), 120.78 (d), 35.19 (t), 33.72 (t), 28.95 (t), 22.35 (t), 15.39 (q), 13.98 ppm (q); IR (neat): $\tilde{\nu} = 3049$ w, 3023 w, 2959 m, 2927 m, 2871 m, 2856 m, 2730 w, 1912 w, 1898 w, 1803 w, 1772 w, 1703 w, 1626 s, 1598 m, 1568 m, 1511 m, 1502 m, 1455 m, 1417 m, 1376 w, 1363 w, 1306 w, 1260 w, 1240 w, 1192 m, 1168 s, 1112 m, 1059 m, 1050 m, 1016 m, 975 m, 942 w, 928 w, 885 m, 832 s, 800 m, 748 m, 728 m, 699 w, 660 w, 642 w, 637 w cm^{-1}; UV/Vis (ethanol): λ (ε) = 319 (13600), 270 (19000), 226 (15000), 203 nm (28500); MS (EI): m/z (%): 266 ($[M+1]^+$, 9), 265 ($[M]^+$, 40), 223 (19), 222 (100), 207 (8), 206 (5), 91 (8), 90 (5), 89 (3), 77 (3).

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