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Electro-optical triple-channel sensing of metal cations via multiple signalling patterns

Diego Jiménez, Ramón Martínez-Máñez,* Félix Sancenón and Juan Soto

GDDS, Departamento de Química, Universidad Politécnica de Valencia, Camino Vera s/n, 46071 Valencia, Spain

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Abstract—We described two molecular systems containing tricyanovinyl dyes as signalling subunits and crown ether macrocycles as binding sites, which act as triple-channel sensing receptors. Signalling was observed through UV–vis, fluorescence and electro-chemical measurements. With these three techniques sensing of certain metal cations was achieved via multiple signalling patterns.

The field of synthetic receptors for guest recognition has grown in interest over the last two decades.[1] Additionally the related field of chemosensing has been rising in parallel.[2] Chemosensors have been designed by coupling (covalently or noncovalently) binding sites for the selective coordination of certain guest and signalling subunits for the transduction of the binding event into an observable signal. In pursuit of this idea, chromogenic,[3] fluorogenic[4] or electro-chemical[5] molecular chemosensors have been developed. A main goal in this approach is that of selectivity. In traditional chemosensors usually only two states are observed corresponding to the change (or lack of change) of a certain signal that is directly related to the presence (or absence) of certain species. This might limit somehow the use of the receptor because the transduction of the coordination event is carried out traditionally via one single channel. In contrast to this classical single-signalling approximation, we were interested in checking the use of multi-channel signalling receptors as potential guest reporters via multiple signalling patterns. This is an unfamiliar area because relatively few examples describing coordination processes via multi-channel signalling have been reported.[6] Specifically, as we report here, the development of triple chromogenic, fluorogenic and electro-chemical signalling molecular sensors is, as far as we know, an unexplored subject.

The systems $\mathbf{L^1}$ and $\mathbf{L^2}$ were chosen to develop triple-channel systems because of their unique optical and electro-chemical properties: they contain a tricyanoethylene group, which is simultaneously a redox-active group and an acceptor moiety in the amino-phenyl-tricyanoethylene chromo/fluorophore (see Fig. 1). Despite their easy synthesis and their extensive application in other fields, tricyanovinyl dyes have scarcely been used for sensing purposes.[7] The synthesis of $\mathbf{L^1}$ and $\mathbf{L^2}$ involved the reaction of 1.5 equiv of tetracyanoethylene with 1 equiv of the corresponding aza–oxa ($\mathbf{L^1}$) or aza–thia–oxa ($\mathbf{L^2}$) macrocycle in warm DMF (60 °C) during 90 min following by purification by column chromatography on silica gel. Both receptors were isolated as dark-brownish solids, their ^{1}H, ^{13}C NMR and mass spectra data being consistent with the proposed formulation.[8]

The visible spectra of $\mathbf{L^1}$ and $\mathbf{L^2}$ in acetonitrile solutions (1.0×10^{-4} mol dm^{-3}) are characterized by bands centred

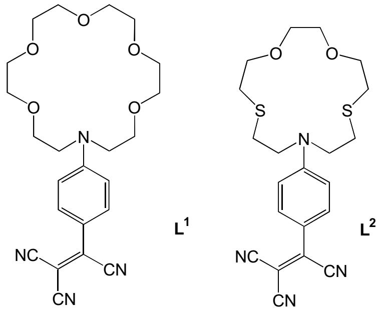

Figure 1. Chemical structures of $\mathbf{L^1}$ and $\mathbf{L^2}$.

Keywords: Chemosensors; Electro-optical sensing; Triple signalling; Pb^{2+} detection; Hg^{2+} detection.

* Corresponding author. Tel.: +34-963877340; fax: +34-963879349; e-mail: rmaez@qim.upv.es

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Figure 2. Colour variation observed in acetonitrile solutions of $\mathbf{L}^2$ ($[\mathbf{L}^2] = 1.1 \times 10^{-4}$ mol dm^{-3}) in the presence of 1 equiv of certain metal cations. From left to right: **L**, Ag^+, Cd^{2+}, Cu^{2+}, Fe^{3+}, Hg^{2+}, Pb^{2+}, Zn^{2+}.

at 520 and 518 nm, respectively ($\varepsilon = 27,500$ L mol^{-1} cm^{-1} for $\mathbf{L}^1$ and $\varepsilon = 26,900$ L mol^{-1} cm^{-1} for $\mathbf{L}^2$), probably due to a charge transfer process from the donor nitrogen atom of the anilinium group to the acceptor tricyanovinyl moiety. Addition of equimolar quantities of Li^+, Na^+, K^+, Ca^{2+}, Ba^{2+} and Mg^{2+} cations to acetonitrile solutions of $\mathbf{L}^1$ produced negligible changes in the UV–vis spectrum. Addition of heavy metals such as Cu^{2+}, Cd^{2+} and Hg^{2+} also resulted in no change. Colour variation (shift of the absorption band from 520 to 470 nm) was selectively observed upon addition of the metal cation Pb^{2+}.[9] Selectivity was moved towards Hg^{2+} by using the aza–thia–oxa crown containing receptor $\mathbf{L}^2$.[10] Thus red-pink acetonitrile solutions of $\mathbf{L}^2$ (1.0×10^{-4} mol dm^{-3}) changed selectively to yellow upon addition of Hg^{2+} (hypsochromic shift from 518 to 400 nm, see Fig. 2).[11] Other metal cations tested (Li^+, Na^+, K^+, Ca^{2+}, Ba^{2+}, Mg^{2+}, Cd^{2+}, Pb^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Ag^+) induced no significant changes. Additionally the UV–vis titration experiments for the systems Pb^{2+}–$\mathbf{L}^1$ and Hg^{2+}–$\mathbf{L}^2$ showed clear isosbestic points that indicate the formation of 1:1 ligand-to-metal complexes.[12] The $\log K$ for the formation of the $[Pb(\mathbf{L}^1)]^{2+}$ and $[Hg(\mathbf{L}^2)]^{2+}$ complexes through nonlinear least-squares treatment of the titration profiles were 6.3 and 7.7, respectively.

The compounds $\mathbf{L}^1$ and $\mathbf{L}^2$ are fluorescent in acetonitrile and, upon excitation at 467 nm for $\mathbf{L}^1$ and 450 nm for $\mathbf{L}^2$, unstructured emission bands centred at 605 and 600 nm, respectively, were observed. Changes in the fluorescence emission intensity upon addition of 1 equiv of the corresponding metal cation are shown in Table 1. The compound $\mathbf{L}^2$ is highly selective and an enhancement of the emission intensity (90%) was only observed in the presence of Hg^{2+}. In contrast the behaviour of $\mathbf{L}^1$ was less specific. An important enhancement (45%) was observed with Pb^{2+} and in addition a remarkable emission quenching was found in the presence of the Cu^{2+} and Fe^{3+} cations.

Table 1. Absorption λ_{max} for $\mathbf{L}^1$ and $\mathbf{L}^2$ and fluorescence emission intensity variation (in % on that of the receptor) obtained for $\mathbf{L}^1$ and $\mathbf{L}^2$ upon addition of metal cations in acetonitrile solutions

	$\mathbf{L}^1$		$\mathbf{L}^2$	
	λ_{max} (nm)	Em (%)[a]	λ_{max} (nm)	Em (%)[a]
Ag^+	520	<5	518	<5
Cd^{2+}	520	<5	518	<5
Cu^{2+}	520	↓16[b]	518	<5
Fe^{3+}	520	↓22[b]	518	<5
Hg^{2+}	520	<5	**400**	↑90[b]
Pb^{2+}	**470**	↑45[b]	518	<5
Zn^{2+}	520	↑10	518	<5

[a] Variation in the fluorescence intensity (%) compared to that of the corresponding receptor.

[b] The arrows pointing upwards and downwards indicate increase and quenching of the emission intensity, respectively.

The electro-chemical response of both receptors $\mathbf{L}^1$ and $\mathbf{L}^2$ was less selective. They showed a reversible one-electron reduction process at −0.69 and −0.66 V versus SCE, respectively (acetonitrile solutions containing 0.25 mol dm^{-3} $Bu_4N^+PF_6^-$ as supporting electrolyte and graphite as working electrode), which can be ascribed to the reduction of the cyanovinyl group. The electro-chemical response of $\mathbf{L}^1$ and $\mathbf{L}^2$ in the presence of certain metal cations can be found in Table 2. Remarkable large anodic shifts of near 370 mV were found for Hg^{2+}, Pb^{2+} and Fe^{3+} with $\mathbf{L}^1$ and for Hg^{2+} and Pb^{2+} with $\mathbf{L}^2$. The cations Cd^{2+} and Zn^{2+} induced a less significant redox shift and Ag^+ and Cu^{2+} gave unremarkable variation.

A remarkable aspect is that, in their molecular interaction with metal cations, $\mathbf{L}^1$ and $\mathbf{L}^2$ gave a somewhat different response in the three available electro-chemical, chromogenic or fluorogenic transduction channels. Those responses directly depend on each particular coordination–transduction process. In this respect, optical transduction (hypsochromic shift) should only be observed if there is a strong interaction of the metal with the anilinium nitrogen (the donor group involved in the charge transfer band at 520 nm),[13] whereas electro-chemical transduction is related to the coulombic interaction between the reduced form of the redox-active group and the metal cation.[14] Thus, the interaction of a certain metal cation with remote binding sites such as the oxygen and sulfur atoms or the cyano groups would give an electro-chemical but not an optical response. Also noticeable is that, especially for $\mathbf{L}^1$, the response obtained by fluorescence is also somehow different to that found chromogenically. Thus, coordination to the aniline nitrogen by Pb^{2+} induced emission enhancement, probably due to the inhibition of a photo-electron transfer mechanism, which is effective in the uncoordinated receptor. Additionally, other cations such as Fe^{3+} induced significant quenching probably via coordination to remote sites other than the anilinium nitrogen, and through interaction with the photo-excited $\mathbf{L}^1$ receptor by way of energy or photo-electron transfer processes.

Table 2. Anodic shifts (ΔE in mV) obtained for $\mathbf{L}^1$ and $\mathbf{L}^2$ in the presence of metal cations in acetonitrile solutions

	$\Delta E(\mathbf{L}^1)$[a]	$\Delta E(\mathbf{L}^2)$[a]
Ag^+	10	17
Cd^{2+}	170	120
Cu^{2+}	40	25
Fe^{3+}	340	240
Hg^{2+}	370	340
Pb^{2+}	360	330
Zn^{2+}	160	140

[a] $\Delta E(\mathbf{L}^n) = E(\mathbf{L}^n + M^{n+}) - E(\mathbf{L}^n)$.

Table 3. Correlation between macroscopic events and signalling patterns for $\mathbf{L}^1$

$\Delta E > 300\,\text{mV}$	Colour variation	Quenching of emission	Information (presence of)
Yes	Yes	No	Pb^{2+}
Yes	No	No	Hg^{2+}
Yes	No	Yes	Fe^{3+}

Another notable aspect is that multi-channel signalling receptors might lead to the acquisition of multiple signal expressions by using single molecular entities. Thus, in traditional sensing the transduction of the coordination event is usually observed via one unique channel (colour change, emission fluorescence variation or redox shift) and only two states can be observed corresponding to the change (Yes) or not (No) of a certain macroscopic signal that is directly related to the presence of a certain guest. By using dual, triple or multi-channel signalling several Yes and No combinations are possible potentially giving rise to several signalling patterns. This is exemplified in Table 3, which shows a simplified analysis of the equivalence between triple-channel signalling and information patterns when using the receptor $\mathbf{L}^1$. Thus a Yes/Yes/No output pattern (ΔE larger than 300 mV/colour variation/emission quenching) would only be observed in the presence of Pb^{2+}. In the absence of lead (no colour variation), Yes/No/No and Yes/No/Yes patterns would be observed in the presence of Hg^{2+} and Fe^{3+}, respectively.[15] Thus $\mathbf{L}^1$ acts as a prototype of a molecular receptor capable of sensing several single guests via multi-signalling combinations.

In summary, tricyanovinyl $\mathbf{L}^1$ and $\mathbf{L}^2$ receptors are the first described electro-optical signalling receptors demonstrating metal interaction via a triple-channel transduction. Despite the fact that in complex mixtures the transduction process would be more complicated, Table 3 illustrates the possibility that a different guest could switch on different signalling channels, opening the door to multiple information and guest reporting via signalling patterns by the use of a single molecular receptor.

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8. Receptor $\mathbf{L}^1$. Flash chromatography (dichloromethane/acetonitrilie 8:2 v/v) on silica gel gave a dark reddish solid. Yield 68%. ^1H NMR (300 MHz, $CDCl_3$) δ: 3.53–3.64 (m, 16H), 3.73 (t, $J = 4.7$ Hz, 4H), 3.80 (t, $J = 4.7$ Hz, 4H), 6.80 (d, $J = 9.4$ Hz, 2H), 8.00 (d, $J = 9.4$ Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 51.80, 68.40, 70.61, 70.72, 70.76, 70.92, 112.74, 113.84, 114.08, 114.47, 117.54, 132.92, 137.10, 154.31. MS (FAB^+) m/z (rel intensity) 440 (M^++1, 100). HRMS calcd for $C_{23}H_{28}N_4O_5$ 440.2060, found 440.2057.
   Receptor $\mathbf{L}^2$. Flash chromatography (dichloromethane) on silica gel gave a dark reddish solid. Yield 58%. ^1H NMR (300 MHz, $CDCl_3$) δ: 2.75 (t, $J = 4.8$ Hz, 4H), 2.89 (t, $J = 7.9$ Hz, 4H), 3.62 (s, 4H), 3.76–3.83 (m, 8H), 6.70 (d, $J = 9.4$ Hz, 2H), 8.04 (d, $J = 9.4$ Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 29.65, 31.88, 52.40, 70.64, 74.30, 112.54, 113.58, 113.84, 114.36, 117.76, 133.14, 137.51, 153.03. MS (FAB^+) m/z (rel intensity) 429 (M^++1, 100). HRMS calcd for $C_{21}H_{24}N_4O_2S_2$ 429.1419, found 429.1426.
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15. Some other combinations are possible; for instance and despite the low quenching found for copper a No/No/Yes combination would be observed with Cu^{2+}; a No/No/No pattern but with variations of ΔE of ca. 100 mV can indicate the presence of Cd^{2+} or Zn^{2+} cations.