Controlled Multi-Stage Recognition of Guests Using Orthogonal Electro- and Photochemical Inputs

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Molecular devices[1] provide direct access to highly miniaturized components such as logic gates,[2] switches,[3] molecular shuttles,[4] and information storage.[5,6] One powerful tool for the creation of these devices is the control of supramolecular interactions via external inputs,[7,8] including such diverse stimuli as chemical, electrochemical, and photochemical signals. Of these stimuli, electrochemical and photochemical inputs and outputs are among the easiest to interface to macroscopic systems, making them amenable to the multi-scale engineering required for the eventual creation of pragmatic devices.

In recent studies there have been many examples of molecular devices that utilize either photochemical[9] or electrochemical[10] inputs to control their function. These systems, however, have generally relied on two-state switching (on−off) for individual supramolecular functions. One way that the versatility of these devices can be enhanced is through the use of multi-state systems. For example, a three-pole supramolecular switch was reported which used TTF in its three stable electrochemical states.[11] This diversity of function can be further expanded through factorial combinations of orthogonal input stimuli that possess two or more states each.[12,13] This results in a device with a vastly increased number of possible discrete states (i.e., the product of the number of possible states for each input).

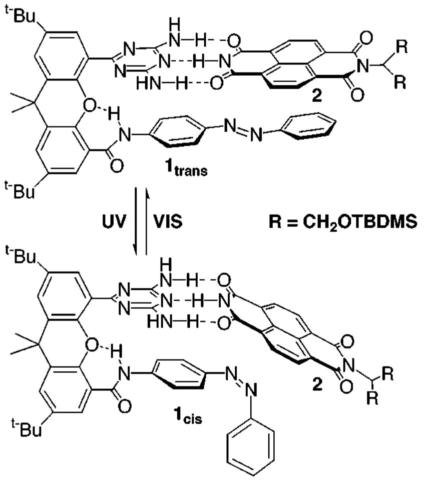

Figure 1. Predicted host−guest complexes $\mathbf{1{:}2^{ox}}$ (Amber force field)

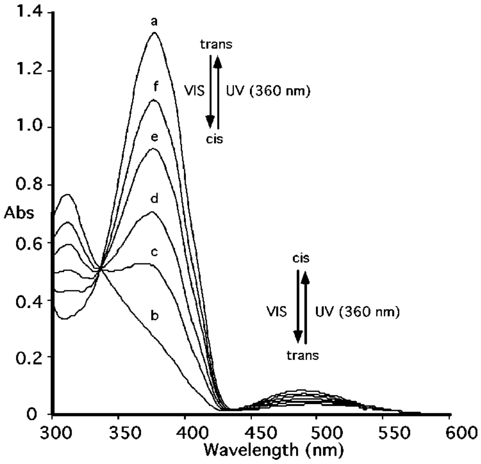

Figure 2. Photoswitching of receptor **1**. Absorption spectra of azo receptor **1** in CHCl$_3$ prior to exposure to UV (line a) and after 5 min of UV exposure (360 nm) (line b). Subsequent exposure to visible light shows the back isomerization (*cis* to *trans*) (lines c−f) (taken at 15 min intervals).

To provide a suitable system with orthogonal inputs, we have created a host−guest dyad in which host **1** possesses two discrete states ($\mathbf{1}_{\mathbf{cis}}$ and $\mathbf{1}_{\mathbf{trans}}$) (Figure 1) that can be switched photochemically. We have paired this host with naphthaldiimide guest **2**[14] that possesses three stable oxidation states ($\mathbf{2}^{\mathbf{ox}}$, $\mathbf{2}^{\cdot-}$, $\mathbf{2}^{=}$). Taken together, this host−guest dyad features six possible binding states.

Initial UV−vis studies on receptor **1** demonstrated the rapid and efficient interconversion of the azobenzene moiety between $\mathbf{1}_{\mathbf{trans}}$ and $\mathbf{1}_{\mathbf{cis}}$ and subsequent reversion to $\mathbf{1}_{\mathbf{trans}}$ (Figure 2). There was no noticeable change in the UV−vis spectrum of **1** (in both forms) in the presence of guest **2**, and ^{1}H NMR studies of the photoswitching in the presence of guest **2** showed efficient reversible isomerization (see Supporting Information). Using the redox active naphthaldiimide derivative **2** as a complimentary guest, the binding constants for the two-component systems were generated. Association constants (K_a) of host **1** and guest $\mathbf{2}^{\mathbf{ox}}$ were determined using NMR titration experiments in CDCl$_3$ (Table

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(1) Blonder, R.; BenDov, I.; Dagan, A.; Willner, I.; Zisman, E. *Biosens. Bioelectron.* **1997**, *12*, 627−644. Tsivgoulis, G. M.; Lehn, J. M. *Chem. Eur. J.* **1996**, *2*, 1399−1406. Gomez-Lopez, M.; Stoddart, J. F. *Bull. Soc. Chim. Belg.* **1997**, *106*, 491−500. Armaroli, N.; Diederich, F.; Dietrich-Buchecker, C. O.; Flamigni, L.; Marconi, G.; Nierengarten, J. F.; Sauvage, J. P. *Chem. Eur. J.* **1998**, *4*, 406−416. Chambron, J. C.; Sauvage, J. P. *Chem. Eur. J.* **1998**, *4*, 1362−1366. Walter, D. G.; Campbell, D. J.; Mirkin, C. A. *J. Phys. Chem. B* **1999**, *103*, 402−405. Endtner, J. M.; Effenberger, F.; Hartschuh, A.; Port, H. *J. Am. Chem. Soc.* **2000**, *122*, 3037−3046.

(2) Credi, A.; Balzani, V.; Langford, S. J.; Stoddart, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 2679−2681. Desilva, A. P.; Gunaratne, H. Q. N.; Maguire, G. E. M. *J. Chem. Soc., Chem. Commun.* **1994**, 1213−1214.

(3) Pina, F.; Melo, M. J.; Maestri, M.; Ballardini, R.; Balzani, V. *J. Am. Chem. Soc.* **1997**, *119*, 5556−5561.

(4) Murakami, H.; Kawabuchi, A.; Kotoo, K.; Kunitake, M.; Nakashima, N. *J. Am. Chem. Soc.* **1997**, *119*, 7605−7606.

(5) Kawata, S.; Kawata, Y. *Chem. Rev.* **2000**, *100*, 1777−1788.Watanabe, O.; Tsuchimori, M.; Okada, A. *J. Mater. Chem.* **1996**, *6*, 1487−1492. Sekkat, Z.; Knoll, W. *J. Opt. Soc. Am. B* **1995**, *12*, 1855−1867.

(6) Asakawa, M.; Ashton, P. R.; Balzani, V.; Credi, A.; Hamers, C.; Mattersteig, G.; Montalti, M.; Shipway, A. N.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; Venturi, M.; White, A. J. P.; Williams, D. J. *Angew. Chem., Int. Ed.* **1998**, *37*, 333−337. Whitesides, G. M. *Sci. Am.* **1995**, *273*, 146−149. Balzani, V.; Gomez-Lopez, M.; Stoddart, J. F. *Acc. Chem. Res.* **1998**, *31*, 405−414. Amabilino, D. B.; Anelli, P. L.; Ashton, P. R.; Brown, G. R.; Cordova, E.; Godinez, L. A.; Hayes, W.; Kaifer, A. E.; Philp, D.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; Williams, D. J. *J. Am. Chem. Soc.* **1995**, *117*, 11142−11170.

(7) Niemz, A.; Rotello, V. M. *Acc. Chem. Res.* **1999**, *32*, 44−52.

(8) Kaifer, A. E. *Acc. Chem. Res.* **1999**, *32*, 62−71.

(9) Brewer, K. J. *Comments Inorg. Chem.* **1999**, *21*, 201−224. Pollitt, S. K.; Schultz, P. G. *Angew. Chem., Int. Ed.* **1998**, *37*, 2104−2107. Sabbatini, N.; Guardigli, M.; Lehn, J. M. *Coord. Chem. Rev.* **1993**, *123*, 201−228.

(10) Beer, P. D.; Gale, P. A.; Chen, G. Z. *J. Chem. Soc., Dalton Trans.* **1999**, 1897−1909.

(11) Ashton, P. R.; Balzani, V.; Becher, J.; Credi, A.; Fyfe, M. C. T.; Mattersteig, G.; Menzer, S.; Nielsen, M. B.; Raymo, F. M.; Stoddart, J. F.; Venturi, M.; Williams, D. J. *J. Am. Chem. Soc.* **1999**, *121*, 3951−3957.

(12) Matrosova, A. Y. *Autom. Remote Control* **1995**, *56*, 433−440. Assanto, G.; Torelli, I. *Opt. Commun.* **1995**, *119*, 143−148. Kang, H. *IEEE Trans. Neural Network* **1994**, *5*, 812−822.

(13) Willner, I.; Willner, B. *Bioelectrochem. Bioenerg.* **1997**, *42*, 43−57. Doron, A.; Katz, E.; Tao, G. L.; Willner, I. *Langmuir* **1997**, *13*, 1783−1790. Gilat, S. L.; Kawai, S. H.; Lehn, J. M. *Chem. Eur. J.* **1995**, *1*, 275−284.

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Table 1. Binding Constants, Reduction Potentials and Free Energies for Host **1**−Guest **2** Complexes

receptor	K_a^{ox} (M^{-1})[a]	$E_{1/2}^{(1)}$ (mV)[b]	$\Delta G^{(1)}$ (kcal/mol)	$K_a^{\cdot -}$ (M^{-1})	$E_{1/2}^{(2)}$ (mV)	$\Delta G^{(2)}$ (kcal/mol)	$K_a^{=}$ (M^{-1})
none	-	−1063	24.54	-	−1516	35.00	-
$\mathbf{1}_{\mathrm{trans}}$	9750	−1103	25.46	2054	−1548	35.74	591
$\mathbf{1}_{\mathrm{cis}}$	575	−1087	25.09	228	−1529	35.30	136

[a] Determined through NMR titration (23 °C, $CDCl_3$). [b] Concentrations used: $\mathbf{1} = 0.0025$ M, 0.005 M,[17] $\mathbf{2} = 0.000\,5$ M in 0.1 M TBAP solution in CH_2Cl_2 at 23 °C, referenced to ferrocene. Uncertainties for $K_a^{ox} = 5\%$ (from standard error of the titration curve fit), $K_a^{\cdot -}$ and $K_a^{=} = 20\%$ based on ±2 mV for voltammetry.

1).[15,16] The 16-fold decrease in binding for the $\mathbf{1}_{\mathrm{cis}}\cdot\mathbf{2}^{\mathrm{ox}}$ relative to the $\mathbf{1}_{\mathrm{trans}}\cdot\mathbf{2}^{\mathrm{ox}}$ system arises primarily from the loss of the favorable aromatic stacking interactions upon isomerization and is possibly accentuated by unfavorable dipolar interactions between the azo group and the naphthaldiimide guest.

Cyclic and square wave voltammetry were then performed on the *cis* and *trans* host−guest systems to determine the effect of guest redox state on recognition efficiency. The reduction of guest **2** demonstrated the formation of $\mathbf{2}^{\cdot -}$ and $\mathbf{2}^{=}$ as stable redox states. Addition of receptor $\mathbf{1}_{\mathrm{trans}}$ resulted in a movement to more negative reduction potentials for both the first and second reduction. This is indicative of unfavorable interactions that develop between the relatively electron-rich azobenzene group that occur as guest **2** is converted from electron-poor ($\mathbf{2}^{\mathrm{ox}}$) to electron-rich ($\mathbf{2}^{\cdot -}$ and $\mathbf{2}^{=}$). A similar negative change in $E_{1/2}$ is observed upon addition of $\mathbf{1}_{\mathrm{cis}}$, indicative of dipolar repulsion between the electron-rich reduced guests and the azo functionality.

Using electrochemically determined changes in free energy, we were able to determine the K_a's of receptor **1** with guest **2** in all three oxidation states (Figure 3).[18] As shown in Figure 4, these six binding states possess five distinct affinities (with the $\mathbf{1}_{\mathrm{cis}}\cdot\mathbf{2}^{\mathrm{ox}}$ and $\mathbf{1}_{\mathrm{trans}}\cdot\mathbf{2}^{=}$ possessing experimentally indistinguishable affinities), spanning a 70-fold range.[19] More significantly, analogous to numerous macroscopic devices such as dimmer switches and volume controls, these affinities are approximately equally spaced exponentially through the entire dynamic range between the two extremes. This ability to control recognition in a finely tuned stepwise fashion allows the potential fabrication of highly complex and tunable systems.

In summary, we have demonstrated the creation of a single host−guest dyad that possesses six states featuring five discrete binding affinities. These affinities are equally spaced exponentially over a wide range, demonstrating our ability to finely tune recognition properties using external stimuli. We are currently exploring the attachment of this system to surfaces, with the ultimate goal of creating addressable molecular devices.

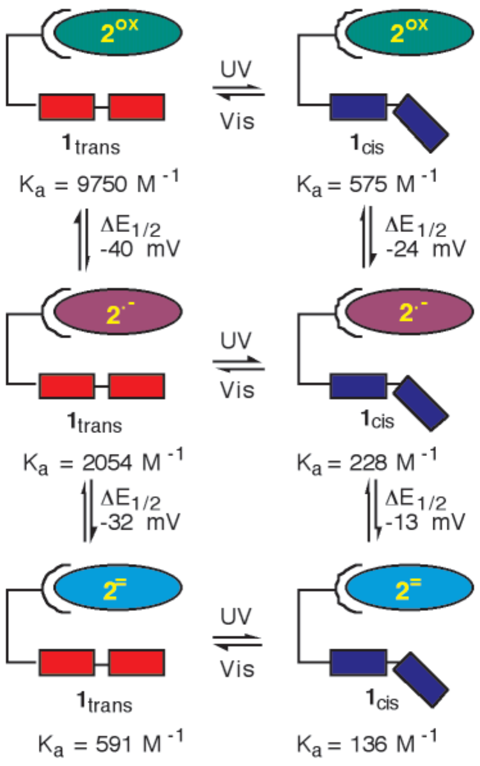

Figure 3. Schematic of redox and photochemical switching of the **1:2** complex.

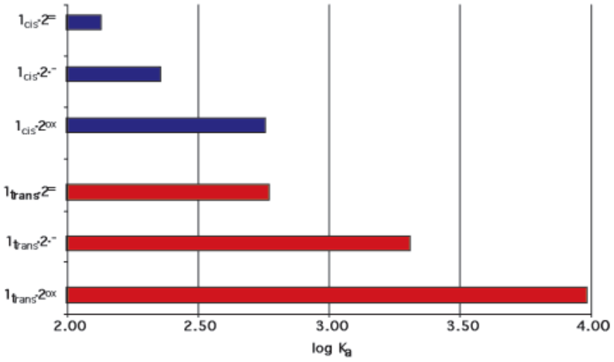

Figure 4. Graph showing binding constants complexes arising from different redox states of guest **2** and conformations of host **1**.

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Supporting Information Available: Synthesis, ^{1}H NMR and IR information for precursors and target molecule, NMR titration graphs, and square wave voltammograms for guest **2**, and the host−guest complexes (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(14) Osuka, A.; Yoneshima, R.; Shiratori, H.; Okada, T.; Taniguchi, S.; Mataga, N. *Chem. Commun.* **1998**, 1567−1568.

(15) A photostationary state of 80% $\mathbf{1}_{\mathrm{cis}}$ was formed during the photoswitching process. The presence of $\mathbf{1}_{\mathrm{trans}}$ was corrected for explicitly when calculating K_a's for all the oxidation states of $\mathbf{1}_{\mathrm{cis}}$.

(16) K_a and $E_{1/2}$ values were determined in similar noncompetitive solvents ($CDCl_3$ and CH_2Cl_2) chosen for their attributes for NMR and electrochemical experiments, respectively. For previous control studies showing that carrier electrolyte does not affect the K_a for host−guest systems of this type, see: Deans, R., Niemz, A., Breinlinger, E., Rotello, V. *J. Am. Chem. Soc*. **1997**, *119*, 10863−10864.

(17) Identical $E_{1/2}$'s were observed between 5 and 10 equiv of added receptor, indicating that maximal shifts (and hence accurate K_a's) were obtained.

(18) Binding constants for the reduced species were calculated by single electron-transfer processes using the following formula: $K_a(\mathrm{red})/K_a(\mathrm{ox}) = e^{(nF/RT)(E_{1/2}(\mathrm{bound})-E_{1/2}(\mathrm{unbound}))}$, where K_a(red) and K_a(ox) are the binding constants for the reduced and oxidized species respectively, and n is the number of electrons involved in the redox step (1 in each of the reductions). The K_a for the $\mathbf{1}\cdot\mathbf{2}^{=}$ complex was obtained using the K_a derived for the $\mathbf{1}\cdot\mathbf{2}^{\cdot -}$ complex as K_{ox}.

(19) Repeated photochemical and electrochemical cycles (up to five) showed no measurable change in any of the switching processes.