Vol. 29 | Núm. 3 | Págs. 108 - 117 | Agosto 2018
DOI: 10.22201/fq.18708404e.2018.1.63736

THE FASCINATING WORLD OF PHOTOCHEMISTRY. VIDEO TUTORIALS FOR CORE CONCEPTS IN SCIENCE EDUCATION

Abstract

Five open access video tutorials concerning photochemistry for Science education are presented. They address especially teachers and students, but can serve also for making photochemistry accessible to the wide public. The common format of the five tutorials is a dialogue between the young layman Niklas and a young scientist who introduces him into different topics of photochemistry. These topics correspond to three common core concepts in worldwide Chemical education: *structure/property-relationships, equilibrio,* and *energy.* Teaching recommendations are given, as to how the tutorials can be beneficial for Science lessons.

Key words: video tutorial, curricular integration, core concepts, photochemistry, model experiment, ground State, excited State, molecular switch, isomerization.

EL MUNDO FASCINANTE DE LA FOTOQUÍMICA. VIDEO TUTORIALES PARA CONCEPTOS BÁSICOS EN LA EDUCACIÓN CIENTÍFICA

Resumen

Se presentan cinco tutoriales en vídeo de acceso abierto sobre fotoquímica para la educación científica. Se dirigen especialmente a profesores y estudiantes, pero también pueden servir para hacer accesible la fotoquímica al público en general. El formato común de los cinco tutoriales es un diálogo entre el joven laico Niklas y un joven científico que lo introduce en diferentes temas de la fotoquímica. Estos temas corresponden a tres conceptos básicos comunes en la educación química mundial: *estructura / propiedad-relaciones, equilibrio y energía*. Se dan recomendaciones de enseñanza sobre cómo los tutoriales pueden ser beneficiosos para las lecciones de Ciencias.

Palabras clave: video tutorial, integración curricular, conceptos básicos, fotoquímica, experimento modelo, estado fundamental, estado excitado, interruptor molecular, isomerización

Autores: Rainer Brunnert, Claudia Bohrmann-Linde, Nico Meuter, Nuno Pereira Vaz, Sebastian Spinnen, Yasemin Yurdanur and Michael W. Tausch

"**The fascinating world of photochemistry**",
Rainer Brunnert, Claudia Bohrmann-Linde, Nico Meuter, Nuno Pereira Vaz,
Sebastian Spinnen, Yasemin Yurdanur and Michael W. Tausch
Vol. 29 | Núm. 3 | Págs. 108 - 117 | Agosto 2018
DOI: 10.22201/fq.18708404e.2018.1.63736

THE FASCINATING WORLD OF PHOTOCHEMISTRY VIDEO TUTORIALS FOR CORE CONCEPTS IN SCIENCE EDUCATION

Introduction

It has become common place that a human being experiences **photoprocesses** every day, which are light-induced Chemical, physical, or biological phenomena. Simply think of the colour perception processes within the eye, energy from solar panels, photosynthesis, phosphorescent stars in children's bedrooms, or the fluorescent markers in banknotes. Even though they have a great significance in chemistry (Albini, 2016), photoprocesses still play a minor role in worldwide Science education. Therefore, internationally usable teaching materials for this future-relevant topic are

In our last article ¡n this journal (Tausch, Meuter, and Spinnen, 2017), we emphasized the relevance of the excited State within photochemistry. In this sense, a series of five educational video tutorials (Tausch, Bohrmann-Linde, Meuter, et al., 2017) have been created. They are provided for free via Beilstein TV (http://www.beilstein.tv). All five of them deal with a different topic involving light. At their respective cores, however, the clips deal with both a scientifically consistent and an experimentally convincing approach to the excited State.

Purpose of the video tutorials

In each tutorial, one relevant aspect of photochemistry has been singled out and didactically reduced. Thus, laypersons, students, and scientists are enabled to join the protagonist, young layman Niklas, on his journey into different areas of photochemistry. These entertaining travels into scientific *térra incógnita* have a duration of approximately five minutes.

These videos have been produced for two main reasons. First of all, teachers can use all of the tutorials for their Science lessons, as many of the discussed photochemical concepts overlap greatly with core concepts within Science education syllabi. They can, for example, be used as **starting points into an understanding of everyday** phenomena, as further research input in scientific **fields that have been dealt with before, or as tools with** certain gaps which, in turn, can be filled by **students' research and preparations. Second, there is the** entertaining yet scientifically correct **presentation of expert knowledge in the field of light-involving** Chemical processes.

Five video tutorials - generic features

The five tutorials cover different aspects of photochemistry: "Light turns ON and OFF: A photoactive molecular switch." (Niklas/Nuno), "What is a photon? Particle-wave duality." (Niklas/Claudia), "Unequal equilibria: Thermodynamic equilibrium vs. photostationary State." (Niklas/Yasemin), "A Chemical chameleon: Molecular environment and solvatochromism." (Niklas/Sebastian), and "Underground minigolf: Colour by light emission." (Niklas/Nico).

All of them abide by the same generic pattern: At the beginning of each clip, Niklas, who takes a keen interest in everyday phenomena and who has a comparably great urge to find out the scientific explanations behind them, presents a current everyday phenomenon to the audience. In a peer, a young photochemist, who takes his questions seriously and who explains the Science background of the phenomenon to him. This main part of the clips features a reasonable theoretical background explanation, certain experiments, and a conversation at eye-level. Additionally, energy models, molecular models, animations, and diagrams contribute vitally to the explanation process. Finally, Niklas rounds off the tutorial by establishing a proper frame for the narrative.

Tutorial 1: "Light turns ON and OFF: A photoactive molecular switch."

Figure 1: Niklas with photochromic glasses

In this clip, Niklas wants to take a look behind the scenes of photochromic glasses (Fig. 1 and Fig. 2). It is Nuno who guides Niklas into the world of **photoactive molecular switches.** He explains to Niklas that - even though there is no photoactive molecular switch in his glasses -there exist photosensitive molecules such as spiropyrane which change their structure when exposed to light of a certain wavelength (Fig. 3). In this case, the colourless spiropyrane switches by irradiation with violet light into its coloured isomer merocyanine. This process is a reversible one as thermal energy or light of another certain wavelength, in this case green light, can switch the merocyanine isomer back into the spiropyrane isomer. Nuno employs an 'intelligent' foil in order to visualize the process: He "draw[s] with nothing but light", as Niklas puts it, turning the embedded molecular switch on, only to turn it off by means of a green light torch, for one thing, and hot water, for another. Furthermore, Nuno uses molecular models of the aforementioned photoactive molecular switch in order to show Niklas what scientists understand by **isomerism** and how this gives rise to a new molecular structure with new properties. Additionally, they talk about how the new shape of molecules brings about a change in the molecule's chromophore, resulting in a different light absorption and, consequently, in a different colour. All of this again leaves Niklas on a higher level of understanding (cf. Krees and Tausch, 2010 for an additional animation).

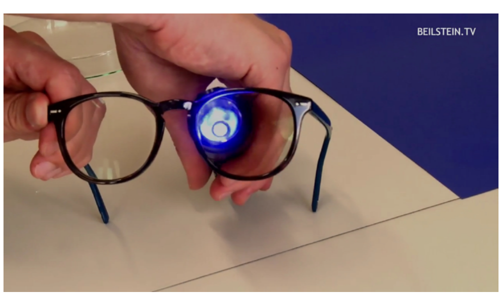


Figure 2 (left): Switching on the photochromic glasses

Figure 3 (right): Nuno and Niklas in the photo-lab

Educación Química
Vol. 29 | Núm. 3 | Págs. 108 - 117 | Agosto 2018
DOI: 10.22201/fq.18708404e.2018.1.63736

Corresponding key terminology: photoactive molecular switch, photosensitive molecules, photochromic substances, switching with UV light and green light, drawing with light, 'intelligent' foil, light absorption and perceived colour, ¡somerism, chromophore, spiropyrane, merocyanine.

Tutorial 2: "What is a photon? Particle-wave duality."

In the introductory part of this video, Niklas raises the question how photons interact with molecules. He himself uses the beautiful phenomenon of a rainbow to convey his questions about this topic to the viewer (Fig. 4).

Figure 4: Niklas wondering about rainbows

Most interestingly, the setting of this video tutorial is not a laboratory, but the *Waldfrieden Sculpture Park Wuppertal,* founded by the renowned British artist Tony Cragg, who uses this location to exhibit his artwork, among them a sculpture called "Photon". Here Niklas meets Claudia, who presents to him the idiosyncratic nature of a photon, that is, a quantum object, which she pragmatically defines as "the smallest indivisible energy package of light" (Fig. 5 left). In order to discuss the partióle quality of a photon she refers to a reflection experiment. To highlight the fact that a photon also comprises wave properties, Claudia explains the outcome of a diffraction grating experiment to Niklas. A joint visit to the sculpture "Photon" then helps Niklas to apply his newly gained knowledge when he interprets the sculpture, which seemingly combines both wave and partióle properties in an artistic way (Fig. 5 right). The discussion then centres around what happens when a photon is absorbed by a molecule, for example when a spiropyrane molecule is promoted to an excited State. Even though Niklas has now accepted the complex nature of a photon, some questions remain, as it is quite complex to comprehend the properties of these tiny energy packages. Or, as artist Tony Cragg has put ¡t: "The world we see around us ¡s only the tip of the iceberg. How are we supposed to imagine a photon [...]? We can only see an object if light bounces off it and goes into our eye. But we are always attempting to see underneath the surface" (Cragg and Austen, 2011). It remains to be seen to what extent future technological developments will do away with the last remaining uncertainties and provide both teachers and students with satisfactory answers as to what is "underneath the surface".

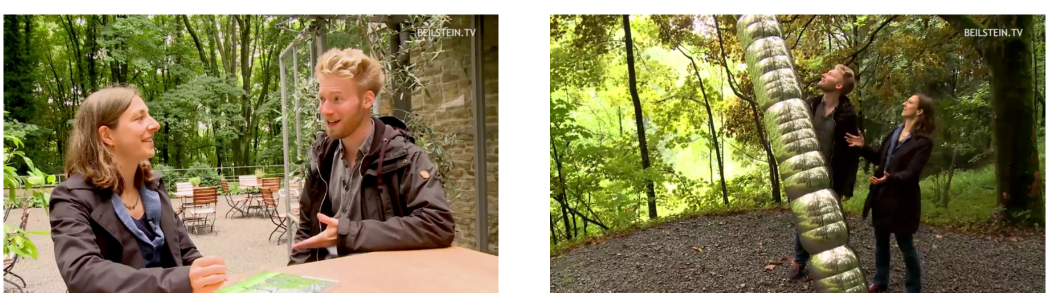


Figure 5: Niklas and Claudia follow the light: Scientific discussions and the joint interpretation of art

Vol. 29 | Núm. 3 | Págs. 108 - 117 | Agosto 2018
DOI: 10.22201/fq.18708404e.2018.1.63736

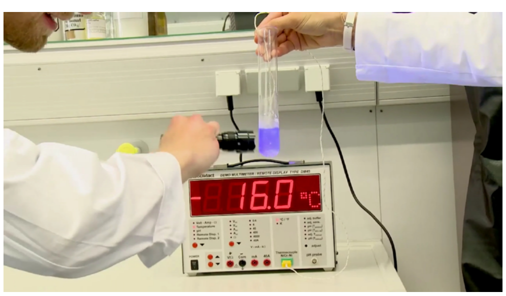
Corresponding key terminology: photon, particle-wave-duality, the nature of a quantum object, artistic interpretation, electronically excited State, ground State, photon absorption.

Tutorial 3: "Unequal equilibria: Thermodynamic equilibrium vs. photostationary State."

Figure 6: Niklas trying to keep his balance

In this clip, the protagonists elabórate on the idea of a **specific Chemical equilibrium - the photostationary State.**

Before exploring the content matter, the idea of different balances in certain everyday situations is brought up by Niklas (Fig. 6) - "but is there also a *Chemical* balance?" Having raised this question, he seeks help with Yasemin. By means of the aforementioned spiropyrane-merocyanine-equilibrium, the two of them conduct a sequence of experiments (Fig. 7). First, they irradíate spiropyrane Solutions at different temperatures and find out that they all turn from colourless to blue in an equally quick way. Flowever, the hotter the solution, the more quickly the blue colour fades. Now Niklas wonders why the colour vanishes at all - and why at different rates. Based on the experiments, Yasemin explains to Niklas the concepts of the two ¡nfluences affecting the equilibrium. The **photostationary State** (photo-steady State) ¡s the overlapping of the light-driven reaction that promotes the formation of merocyanine, and the simultaneously occurring thermal back reaction from merocyanine to spiropyrane. This is further emphasized experimentally by irradiating a spiropyrane solution at -16 °C (2 °F) (Fig. 8). Thus, Niklas' question was answered satisfactorily (cf. Krees and Tausch, 2010 for a more detailed explanaron of the photostationary State).



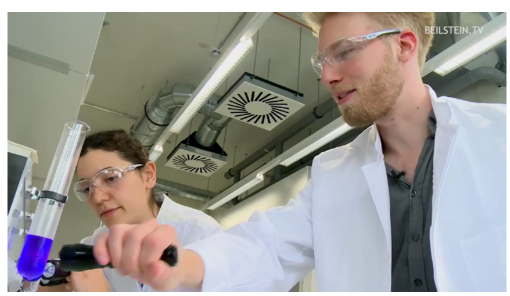


Figure 7 (left): Yasemin and Niklas conducting an experiment

Figure 8 (right): Irradiation of a spiropyrane-solution at -16 °C

Corresponding key terminology: ground State, excited State, thermodynamic equilibrium (chemical equilibrium), photostationary State (photo-steady State), spiropyrane, merocyanine, molecular switch, Le Chátelier's principie.

Vol. 29 | Núm. 3 | Págs. 108 - 117 | Agosto 2018
DOI: 10.22201/fq.18708404e.2018.1.63736

Tutorial 4: "A Chemical chameleon: Molecular environment and solvatochromism."

Figure 9: A chameleon starring in the introduction of this video

Here Niklas establishes a bridge between a living animal, a chameleon, which *allegedly* changes its colour based on the surrounding and a Chemical 'chameleon', which does so *indeed* (Fig. 9). It ¡s Sebastian who sheds some light on this topic by dissolving the compound spiropyrane in three different solvents. Having irradiated the three different Solutions and switched the colourless spiropyrane into the coloured isomer merocyanine, the two of them now observe three different colors (red, purple, blue) (Fig. 10). Niklas wonders: "Why's that? I thought you've only put *one kind* of molecule into all of these test tubes?" Sebastian explains the effect of **solvatochromism** to Niklas, using an absorption diagram and an energy level diagram (Fig. 11). The same molecule generates different colours depending on the surrounding solvent molecules. The solvent molecule's ¡nfluence on the energy gaps between the respective highest occupied energy level and the lowest unoccupied energy level of the merocyanine molecule is responslble. Finally, Niklas has found a scientlflc answer to his questlon about the three different colours.

Figure 10 (left): Merocyanine in three different solvents

Figure 11 (right): A conversation between Sebastian and Niklas

Corresponding key terminology: solvatochromism, molecular environment, light absorption and perceived colour, molecular switch, highest occupied energy level (highest occupied molecular orbital HOMO), lowest unoccupied energy level (lowest unoccupied molecular orbital LUMO), spiropyrane, merocyanine.

Tutorial 5: "Underground minigolf: Colour by light emission."

The context of this tutorial is an underground minigolf course. Accordingly, this clip takes its point of origin in Niklas *Figure 12: Underground Minigolf courses* wondering how the light from the dark violet tubes can "create all of these bright colours" that he perceives on the fashionable Wuppertal minigolf course (Fig. 12). In this case, Nico helps Niklas understand the underlying concepts of **fluorescence** and **phosphorescence** by employing a model animation. In conjunction with a parallel luminescence experiment, the animation comprises detailed explanations concerning the Stokes Shift and the additional bathochromic shift by phosphorescence. It becomes evident that the **emitted photons are less energetic than the absorbed onesr** However, Nico challenges Niklas' newly-acquired knowledge by showing him first-hand, how he can turn the aforementioned principie upside down: The **cognitive conflict** is created by Nico pointing a láser beam on a small snap-on glass containing a seemingly ordinary solution - however, most astonishingly, the *green* of the láser beam turns ¡mmediately ¡nto a *blue* fluorescent track ¡n the solution (Fig. 13 and Fig. 14). That is, the energy of the emitted photons now contains more energy than the energy of the absorbed photons **(Anti-Stokes Shift).** In the following discussion between Niklas (who, unfortunately, failed with his intelligent guess that the extra energy could stem from a hot solution) and Nico, the latter uses a didactically reduced energy diagram in order for Niklas to understand how the blue colour comes into being.

Figure 12: Underground Minigolf courses

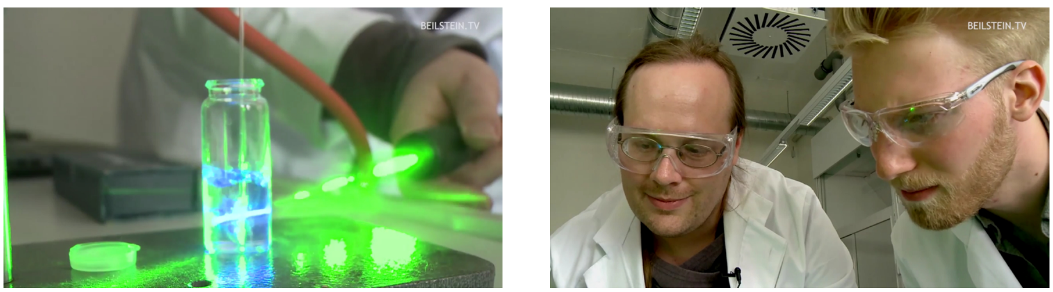


Figure 13 (left): From green to blue: Anti-Stokes Shift

Figure 14 (right): Excited men at work: Nico and Niklas

Corresponding key terminology: colour by light emission, fluorescence, phosphorescence, invisible UV light, visible light, model animation, ground State, electronically excited State, vibrational States, triplet triplet annihilation, photon down- and upconversion, Stokes Shift, Anti-Stokes Shift.

Video tutorials and core concepts in Science education: implementation recommendations

The three core concepts *structure/property-relationships, Chemical equilibria,* and *energy* can be considered *common* concepts in worldwide higher secondary education. In our research into teaching programs from numerous countries and territories from all over the world (e.g. Argentina, Australia, Austria, Belize, Cañada, Ecuador, Egypt, England, Estonia, Guyana, Hong Kong, India, Ireland, Jamaica, Jordán, Kenya, México, the Netherlands, New Zealand, Nigeria, Portugal, Russia, Scotland, Switzerland, Trinidad and Tobago, Turkey, USA, and Venezuela) we found out that the three core concepts are represented in all of them. By using English as the language in the tutorial, we address an international audience: teachers, students, and laypersons interested in Science.

In a larger sense, the tutorials lay the foundations for an understanding of numerous contemporary technological applications: For example, there are **"hard coatings"** which can heal themselves "based on photoinduced solid-to-liquid transitions" (Zou, Xue, Weis, et al., **2017, 145, 149).** Then there are **nano machines,** whose movement can be controlled solely by radiation with light of different wavelengths. Furthermore, the opening and closing of little **nano containers,** possibly releasing a drug in a desired location within the human body, can be controlled in a comparable way (Feringa, **2017).**

Teaching recommendations

When working on any of the following core concepts, the students might ask themselves what light or what a **photon** might be. We think that tutorial 2 "What is a photon?" will prove beneficial when addressing this question. This is the reason why the tutorial is mentioned already here.

Recommendations for core concept 1: structure/property-relationship

The tutorials "Light turns ON and OFF" and "A Chemical chameleon" can be used in this context.

First of all, **isomerism** plays a key role. In Germán school chemistry lessons, teachers typically use three isomers of butanol (i.e. butan-l-ol, butan-2-ol, and 2-methylpropan-2-ol) in a reaction with copper(ll)-oxide. Contrary to the students' expectations the compounds react differently, or not at all. The students will then examine the structure of 'butanol' - and their cognitive conflict is resolved. The switching experiment with the 'intelligent' foil is also a good example of isomerism. While the structural difference of the different butanol isomers is not visible to the naked eye, the observer of the 'intelligent' foil-experiment can easily see a change in colour. This is closely connected to the molecule's structural transformation. Thus, isomerism is presented to the student in an easily accessible way.

Second, there is **colour by light absorption.** Students usually learn that a certain colour molecule causes the perceived colour. Solutions of merocyanine in ethanol, acetone, and toluene show different colours (solvatochromism) - a source of a **cognitive conflict,** "[t]he classic way to develop intrinsic motivation" (Barke, Harsch, and Schmid, 2012, 46). The experiment reveáis that not only the colour molecule is responsible, but also the Chemical environment. Accordingly, merocyanine can be understood as an ¡ndicator for polarity, which ¡s usually not perceptible by visión. The explanation of solvatochromism can pave the way into **molecular orbital theory** - highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO). (For a detailed discussion of structure/property-relationships regarding light absorption and emission cf. Tausch, Meuter, and Spinnen, 2017.)

Recommendations for core concept 2: Chemical equilibria

The tutorials "Light turns **ON** and OFF" and "Unequal equilibria" can be used in this context. It is quite common that students only deal with **thermodynamic equilibria,** often simply called Chemical equilibria, at school and both clips can give insight into a different kind of equilibrium: the **photostationary State.** It might mostly be interesting to compare and contrast it with the already known Chemical equilibrium. Furthermore, as the switching of photoactive **nano machines** and **nano containers** is often based on photostationary States, it might be interesting to investígate the underlying principies of these two kinds of equilibria: thermodynamic equilibrium and photostationary State (cf. core concept structure/property-relationship).

Recommendations for core concept 3: energy

Here, all tutorials can be used because **light** itself is a form of energy that can be easily used by mankind in various ways (Albini, 2016, 245ff; Ávila-Zárraga, 2009). The energy of different light colours is one of the topics in "Light turns ON and OFF" as only violet or UV light switches on and only green light switches off. Students could prepare 'intelligent' foils themselves and experiment with different light colours and find out **which light colour works** (tutorials and further material about how to create these foils: cf. the text tutorial by Krees, 2012 or the video tutorial by Meuter and Tausch, 2015).

The topic of **colour generation by light absorption and emission** is most prominent in "Underground minigolf." Photons carrying different amounts of energy are absorbed and emitted by a certain substance, resulting in what we conceive of as **fluorescence** and **phosphorescence.** Students who have already dealt with the concept of colour caused by light absorption in organic molecules (key word: **chromophore)** can find in this tutorial the mechanisms of colour generation by fluorescence and phosphorescence. They will understand why ¡n both cases the emitted photons are of less energy than the absorbed photons (dow/nconversion of photons). Nevertheless, Nico's experiment ¡n this video shows that an upconversion of photons is also possible. The cognitive conflict arising from this phenomenon can be resolved by the triplet-triplet-annihilation clearly elucidated in the video. Despite the fact that this mechanism oversteps the curricula for higher secondary schools, it contains a high motivation potential due to the very interesting technical applications, for example in solar cells.

Acknowledgment

We acknowledge the Germán Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for supporting the projects Photo-LeNa (TA 228/4-1) and Photo-MINT (TA 228/4-2) "Photoprocesses in Science Education".

Supplement

This article is accompanied by supplementary online material (i.e. further teaching recommendations).

References

Albini, A. (2016). Photochemistry. Past, Present and Future. Berlín: Springer.

Ávila-Zárraga, J. G. (2009). Síntesis fotoquímica mediante luz solar. *Educación Química,* 20(4), 426- 432.

Barke, H.-D., Harsch, G., and Schmid, S. (2012). *Essentials of Chemical Education.* Berlín: Springer. Beilstein-Institut zur Fórderung der Chemischen Wissenschaften. Beilstein TV.

http://www.beilstein.tv/ [consulted 23 October 2017].

Cardellini, L. (2013). Advocating Science for All. An interview with Peter J. Fensham. *Journal of Chemical Education, 90(6),* 735-740.

Cragg, T., and Austen, K. (2011). Sculpting what isn't there. *New Scientist, 211(2823),* 46.

Feringa, B. L. (2017). The Art of Building Small: From Molecular Switches to Motors. Nobel Lecture.

Angewandte Chemie International Edition, 56(37), 11060-11078.

Krees, S. (2012). Prepararon of an 'intelligent' foil on the basis of a molecular switch.

http://www.chemledldaktlk.unl-wuppertal.de/flles/english/2012/workshop_preparation_ of_an_intelligent_foil_engl.pdf [consulted 23 October 2017],

Krees, S., and Tausch, M. W. (2010). Photo-steady State. Exploration of the concept with the substance spiropyrane. Online animation. http://www.chemiedidaktik.uni-wuppertal.de/flashlist/fetch_animation.htm?pLnk=photosteadystate&height=12&width=15 [consulted 23 October 2017].

Meuter, N., and Tausch, M. W. (2015). Preparation of an ,intelligent' foil. Video clip. http://www.chemiedidaktik.uni-wuppertal.de/files/chemie24/videos/intelligente_folie.mp4 [consulted 23 October 2017],

Tausch, M. W., Bohrmann-Linde, C., Meuter, N., et al. (2017). The Fascinating World of Photochemistry. Beilstein TV Tutorials (English), http://www.beilstein.tv/tutorials-english/ [consulted 23 October 2017],

Tausch, M. W., Meuter, N., and Spinnen, S. (2017). Photoprocesses in Chemical Education - Key Experiments for Core Concepts. *Educación Química, 28(3),* 120-126.

Zou, H., Xue, C., Weis, P., et al. (2017). Photoswitching of glass transition temperatures of azobenzene-containing polymers induces reversible solid-to-liquid transitions. *Nature Chemistry, 9,145-151.*

Recepción: 03 de marzo de 2018. Aprobación: 17 de mayo de 2018