Biomimetic behaviour in artificially created active matter that allow deterministic and controlled motility has become of growing interest in recent years. It is well known that phototrophic bacteria optimize their position with respect to light by phototaxis. Here, we describe how our magnetic, photocatalytic microswimmers apparently undergo phototactic behaviour. Since there is no obvious reason for the particles to do so, we analyze different influences and elucidate through experiments and theoretical considerations from which physical circumstances this behaviour originates.
Apparent phototaxis enabled by Brownian Motion

Lukas Niese\textsuperscript{1}, Linlin Wang\textsuperscript{1}, Sayan Das\textsuperscript{2} and Juliane Simmchen\textsuperscript{1}

\textsuperscript{1}Physical Chemistry, TU Dresden, Zellescher Weg 19, 01069 Dresden, Email: juliane.simmchen@tu-dresden.de

\textsuperscript{2}MPI Intelligent Systems, Heisenbergstr. 3 70199 Stuttgart

January 2020

1 Table of content and abstract

Biomimetic behaviour in artificially created active matter that allow deterministic and controlled motility has become of growing interest in recent years. It is well known that pho-
totrophic bacteria optimize their position with respect to light by phototaxis. Here, we describe how our magnetic, photocatalytic microswimmers apparently undergo phototactic behaviour. Since there is no obvious reason for the particles to do so, we analyze different influences and elucidate through experiments and theoretical considerations from which physical circumstances this behaviour originates.

2 Introduction

Tactic behaviour is emerging as one of the most important features in active matter. Its most frequent biological analogue is phototaxis which refers to a light-oriented change of location of a motile organism. Especially phototrophic microorganisms, i.e. bacteria or algae converting water and carbon dioxide to carbohydrates and oxygen, require light to perform photosynthesis and therefore benefit strongly from optimizing the light conditions in their surroundings. Cyanobacteria are capable of distinguishing between different wave lengths and directions of light. This is especially remarkable since bacteria are considered too small to sense gradients across their bodies and rely on detecting variations over time. Schuergers et. al discovered that the unicellular cyanobacterium Synechocystis can directly sense light by using their bodies as tiny microlenses, a mechanism that is known to be also employed by the larger volvox algae.

Biological variability makes understanding the mechanism of phototaxis complicated, including different taxis, the molecular base of photosensors and other strategies employed to detect and subsequently respond to light. Even though a complete understanding of the different mechanisms and their implementations is still to be achieved, first agent based models describe phototactic behaviour, e.g. in colonies of cyanobacteria or use mesoscale dynamics simulations to study the phototactic behavior of self-thermophoretic Janus particles. First artificial creation of tactic behaviours mostly mimic photophobicity, i.e. the response to a gradient of light, as was shown for droplets. Liquid crystal droplets driven helically by molecular motors were shown to respond to irradiation with re-orientation. Microsized approaches include
photo-activated microparticles exposed to an inhomogeneous laser field, carbo-nitride particles following light source, self-electrophoretic silicon nanotrees with TiO$_2$ nanowire heads that enable steering through their self-shading effect and spiropyran terminated polymer particles whose phototactic propulsion is driven by UV-induced interfacial tension gradient. Inspired by this natural behavior, herein we investigate a phenomenon that strongly resembles phototactic motility. Using biological definitions, we can describe this behaviour as scotophobic, positive photokinetic swimming of our artificial, photocatalytic titania based micromotors. Here, elucidate its origins and shed light on the underlying mechanisms that enable this behaviour and give reasons for these mechanisms in phase portraits obtained via boundary element method.

3 Results and Discussion

The light-driven, self-propelled colloids used throughout this manuscript are anatase TiO$_2$ Janus particles covered with a thin Nickel Gold bilayer (see SI Fig. 1). An ultraviolet (UV) light-emitting diode (385 nm) was used as the light source to power the motion. Upon UV irradiation an asymmetric gradient arises by catalytic decomposition of hydrogen peroxide (see Figure 1 A) and sets the particle in motion. The ferromagnetic Nickel layer enables control over the swimming direction, by an external magnetic field (see setup SI Fig. 2 and 3). How the application of UV light and magnetic field effects the motion behaviour of the Au@Ni@TiO$_2$ particles can be seen in Figure 1 B-E.

![Figure 1](image)

Figure 1: A scheme of photocatalytically induces motion B-E track lines of selected particles in 0.5 % H$_2$O$_2$. B no UV light, no magnet; C 100 % UV, no magnet; D 100 % UV, $\vec{B} = 5$ mT; E 100 % UV, $B=5$ mT, with restricted UV area (bright). scale bar 25 µm.
As shown in Figure 1B, in absence of UV light the particles are catalytically inactive. Therefore only passive molecular motion is observed (Brownian Motion). When exposed to light, the photocatalytic reaction produces a product gradient which induces active motion of the microswimmers. Due to the unguided way of movement, the particle tracks display a random walk (Figure 1C), which is best described as enhanced Brownian Motion (BM). By installing an constant magnetic field (MF) on the experiments setup, the particles orient preferentially according to the magnetic field lines and move in straight paths with defined direction (Figure 1D). If the illuminated area is additionally restricted to a narrow stripe, an unexpected swimming behaviour is observed, which is shown in Figure 1E. Herein, the microswimmers, still moving in straight lines, turn around and migrate back towards the higher light intensity, when leaving the irradiated zone. At the first glance, this phenomenon could be understood as a kind of phototaxis. In quest of the distinct cause for the particles’ behaviour, samples were systematically trialed with changes in orientation of MF towards the light stripe, different hydrogen peroxide concentration and intensity of UV light, as well as differences in particle size. In general, the MF was set to a level of $\vec{B} = 5 \text{ mT}$, which ensured homogeneity of field (see SI Fig. 3 field lines) as well as sufficient momentum for stable particle alignment. There were no indications that variations in magnetic field strength could further improve particle guidance. Although major dependency of particle velocity on the magnetic field strength is reported for some microswimmers, there was no significant effect in the probed Au@Ni@TiO$_2$ system. When the MF was reoriented in a way that the particle tracks went diagonally with respect to the light stripe, the apparent phototaxis, was also observable (see SI Fig. 4 different angles and corresponding particle responses). The Nickel thickness had little influence on the response, see SI Fig. 5. Thus the orientation of MF can also be excluded as a critical factor with respect to the phenomenon. After these findings, the main focus of investigation was on testing several particle types, deviating in size and catalytic activity. Four different samples, which are characterized by scanning electron microscopy in Figure 2 were probed. By varying preparation methods, average particles diameters in range from 0.7 µm to 3.5 µm could be
obtained.

Figure 2: SEM pictures of Janus particles with average sizes of 0.7 µm (A), 1.2 µm (B), 1.6 µm (C), 3.5 µm (D) and their velocities (E) in 0.5 % H$_2$O$_2$ solution ($v_m$ - mean velocity at given UV intensity, $v_{max}$ - velocity of fastest particle), scale bar 1 µm.

As shown in Figure 2 E, the mean velocity of the particles motion in absence of UV light (orange bars) is decreasing with larger diameter. This inverse proportionality is expected for passive Brownian swimmers.[8] In contrast, the velocity of active motion did not display any size dependency, as it is the case for normal catalytic swimmers, due to the size-dependant viscous drag force.[8,21] It seems, that the different photo-catalytic properties are predominant against the size related effects of colloidal movement. Each sample originated from a different synthesis, thus various surface properties like grain size, porosity and crystal structure occurred, which are crucial factors for catalysis. Anyhow, the Powder X-Ray Diffraction data show that all samples have anatase as their predominant crystal phase (SI Fig. 1 XRD-patterns). An equal calcining under nitrogen atmosphere let all probes turn their colour from white to black, which indicates free oxygen vacancies for all of them.[29]
Figure 3: Typical pathways of particles, with different average sizes (A 0.7 µm, B 1.2 µm, C 1.6 µm D 3.5 µm) and particle sketches in relative sizes. Scale bar 25 µm.

Besides the differing mean velocities, observations reveal quite massive varieties in the particles’ general swimming behaviour. Figure 3 illustrates some representative track lines for each batch of samples. Most distinctly particles show different tendencies to change their direction. The smallest species, switches its main direction several times within its path, even within the fully irradiated area. Furthermore, this sample type penetrates the dark stripe only for few micrometers. In contrast there were almost no turns occurring in the tracks of the biggest, 3.5 µm sized particles. The intermediate, 1.2 µm and 1.6 µm probes moved in between these extremes and inverted the direction readily after having moved to the dark area. These observations point towards a size dependent effect. A closer look at one of these generic particle tracks is taken in Figure 4 (exemplary for 1.6 µm particle). In B the probes velocity and y coordinate is plotted against the time. In connection with Figure 4 A it gets evident, that the velocity drops when the swimmer crosses to the dark zone and the point of turning coincides with lowest speed. These findings were confirmed in another experiment, where the particles’ tendency to turn back was tested for different velocities and particle’s sizes (4 C). To this end the particle tracks were analyzed regarding the switches position in y direction, upwards to downwards or reverse. This number was averaged over time and plotted against the mean velocity of the observed swimmer. Variation of speed was realized by changing the intensity of UV light from 20 % to
100 % in steps of 20. About 15 particle paths were analyzed for each light condition and batch of samples. Figure 4 C displays the trend that larger or faster moving samples undergo less directional changing. Additionally it could be confirmed that higher peroxide concentration, also leading to higher speed, causes less events of turning (see SI Fig. 6). In general, it is well-understood that the reorientation rate of colloidal particles is determined by the rotational diffusion time $t_{rot} = \frac{8\pi \eta R^3}{k_B T_{inert}}$ which only depends on the particle radius $R$, the solvent viscosity $\eta$ and the thermal energy $k_B T$. This means that larger particles reorient more slowly than smaller particles when they arrive the back point with Brownian motion state. However, Lozano et al. also discuss, that the reorientation rate must respond to the activity (in their case the local light intensity), otherwise no directed motion were possible.

Figure 4: Instantaneous particle velocity depending on vertical position. A, trajectory of an individual micromotor (with imperfection in coverage for better visualization path). B, analysis of instantaneous velocities and y position of coordinates from particle in A. C, shows the tendency of a particle to turn back, depending on its velocity and size. The y alternation indicates the average number of directional changes in y direction per second. This was counted for movement in UV area only.

Looking in detail at the different processes influencing the behavior (see overview SI Fig. 7) we notice that the particle orientation is fixed in the horizontal plane by the magnetic field. Fig. 8 in the SI shows the resulting sinusoidal potential created by the magnetic field that becomes 0 only if the particle’s cap is aligned with B. This is the case for $\phi = n \pi$ meaning any rotation around the y axis maintains the cap orientation parallel to B is allowed. Therefore, the magnetic field fixes $\phi$, while it has no effect on $\theta$. 

7
If the influence of the activity, or velocity of the particles were modelled as a potential, it would have two traps, resulting in two possible \( \theta \) orientations. Similarly, we can plot the measured velocity of a microswimmer depending on its position within the field of view. The light stripe is located approximately between -20 and 20 \( \mu \)m where Figure 5 shows an increased speed up to 65 \( \mu \)m /s. Figure 5 shows clearly that the speed reduces in the zone that corresponds to the edge of the light stripe, where due to a decreased light intensity, the velocity/activity decreases.

In Figure 5 we display the velocity depending on the \( y \)-position and assort the corresponding phase portraits obtained by the boundary element method. The phase portrait for a Janus particle (calculated at surface mobilities \( b_{\text{inert}}/b_{\text{cap}} = 0.6 \)) in different areas of the experiment:

The left phase portrait (blue) indicates that at very low velocity values (that translate into high values for dimensionless apparent weight, \( F \), gravitactic torque, \( T \), on the particle. \( F \) and \( T \) are scaled with respect to the characteristic Stokes drag and the corresponding torque on the particle.) no stable attractor is forming, that means that no preferred orientation for \( \theta \) of the Janus particle is found. Increasing the velocity slightly, characterized by lower values
for F and T, the phase portrait shows a meta-stable saddle point, relatively close to the red attractor. This indicates, that even small random fluctuations can shift the system away from the attractor, making it less stable and enabling a turn into the opposite motion direction, reverting the particle and enabling it to swim back towards the illuminated region. The yellow surrounded phase portrait represents the particle behavior in the illuminated area, where most particles show a high activity and a high swimming velocity (characterized by low values for F and T). It has a dominant red attractor, at about $\pi/2$ which indicates that the angle $\theta$ is stable during the swimming behaviour with a large basin of attraction, therefore a shifting of the particle out of this stable state is only possible in the border region of illumination. Since then we have to consider the horizontal orientation of the particle to be fixed by the magnetic field, the only turn can happen maintaining $\phi$, which results in the particle turning back and swimming towards the light.

4 Conclusion

We report a unexampled behaviour for magnetically guided photocatalytic microswimmers. This behavior consists in crossing a light stripe, followed by a subsequent direction change that leads to 'swimming back to the light' that resembles the biological phenomenon of phototaxis. Studying the different influences that contribute to this behavior, we find that neither the magnetic field nor the peroxide content have important effects on the behaviour. Instead, we identify the particle size as critical factor with its direct influence on the rotational diffusion time, related via the particles’ Brownian motion. Theoretical analysis of the strength of the attractor that leads to a stable swimming angle show that a loss of activity results in a smaller basin of attraction and to a more ready turning when Brownian motion deviates the particle position slightly from the attractor. Due to the constant magnetic field and the magnetization of the particles, this turn can only in vertical direction and is fixed to multiples of $\pi$ and therefore leads to such behaviour. This independent shuttling behaviour can pave the way towards cargo transport mechanisms that work independently of permanent control.
5 Experimental Section

Chemicals:
titanium (IV) isopropoxide (Alfa Aesar Co. Ltd.); dodecylamine (Fluka); formic acid (Sigma Aldrich); titanium (IV) tetrabutoxide (Sigma Aldrich); sodium hydroxide (Gruessing GmbH); sodium chloride (VWR); hydroxypropyl cellulose (Sigma Aldrich) As solvents methanol, acetonitrile and ethanol were used in analytical grade without any additional treatment.

Synthesis of TiO$_2$ microparticles 0.7 µm$^{[25]}$

180 µl distilled water were added to a mixture of 45 ml acetonitrile and 110 ml methanol. After adding 280 mg DDA, the solution was stirred for 10 min using a 500 ml two-necked flask. Subsequently, 1 ml TTIP was added within 5 min using a syringe pump. It was stirred continuously at 600 rpm room temperature for a further 72 h. The resulting suspension was centrifuged at 2000 rpm for 2.5 min, the supernatant was discarded and the precipitate dispersed in 15 ml methanol. The particles were washed 3 times with 15 ml methanol each and then dried for 3 h at 80 °C.

Synthesis of TiO$_2$ microparticles 1.2 µm$^{[25]}$

70 µl distilled water was added to a mixture of 30 ml acetonitrile and 61 ml methanol. After adding 538 mg DDA, the solution was stirred for 10 min at 35°C in a 500 ml two-necked flask. Subsequently, 1 ml TTIP was added within 5 min using a syringe pump followed by 25 min stirring at 40°C. Stirring was continued with 600 rpm at room temperature for a further 72 h. The resulting suspension was centrifuged at 2000 rpm for 2.5 min, the supernatant was discarded and the precipitate redispersed in 15 ml methanol. The particles were thus washed 3 times with 15 ml methanol each and then dried for 3 h at 80 °C.

Synthesis TiO$_2$ microparticles 1.6 µm$^{[5]}$

100 µl of a 0.1 M NaCl solution and 425 µl titanium(IV)tetrabutoxide were added to 25 ml of ethanol. After 18 minutes of stirring, the solution was aged at room temperature for 24 h to promote gel formation. The resulting solid was washed three times with 15 ml ethanol and 15 ml deionized water, and dried for 3 h at 80 °C.

Synthesis TiO$_2$ microparticles 3.5 µm$^{[5,30]}$
1.3 ml titanium (IV) isopropoxide was mixed with 30 ml ethanol and 0.35 ml formic acid. The resulting solution was transferred to a Teflon autoclave, sealed and heated up to 150 °C for 12 h. After chilling to room temperature, the resulting particles were washed three times with 15 ml ethanol and twice with 15 ml deionized water.

**Calcination** Finally, all particles were calcined at 600 °C for 2 h under a nitrogen atmosphere in a tubular oven. The heating rate was 0.5 K per minute.

**Creating Au@Ni@TiO$_2$ janus structures**

Using Langmuir-Blodgett trough$^{[22]}$, monolayers of calcined TiO$_2$ particles were coated with a nickel layer (between 10 nm and 50 nm) and 30 nm gold subsequently using physical vapour deposition.

**Observation of particle behaviour**

To observe the particles behavior in diluted H$_2$O$_2$ the Janus particles were treated as following. The Janus particles were detached from the cover glass using an ultrasonic bath. Some microliters of this suspension were mixed with H$_2$O$_2$ and spread onto a cleaned and plasma-treated cover glass. An inverted optical microscope (Carl Zeiss Mikroskope GmbH) and a “N-Achroplan” 63x/0.95 M27 objective were used for observation. The microscope used was equipped with a Zeiss Colibri LED lamp, which provided additional illumination of the glass plates from the bottom side. So, this bottom side was additionally exposed by UV light (385 nm). To visualize the UV exposed area, it was overlaid with green light (555 nm). With the help of an aperture UV and green light, could be restricted to a rectangle shaped section of the observed area. During the experiment, the radiant power of the UV lamp was varied in the range from 20 % to 100 % (63 mW / 315 mW). The particle behavior was recorded with a Zeiss camera (Axiocam 702 Mono) and a frame rate of 40 fps. A precise analysis of the trajectories was done using the software “fiesta”.$^{[23]}$

**Phase portraits** To obtain phase portraits, first we need a knowledge of the particle velocity $U$ and $\Omega$. This particle velocity comprises of both the effects of self-propulsion and gravity induced sedimentation. The self-propulsion velocity counterpart is obtained by the utilizing the classical theory of diffusiophoresis along with the help of a numerical approach that has been
The contribution due to gravity is obtained directly from the gravitational force and torque acting on the particle. The particle velocity is calculated corresponding to a grid of values of \((h, \theta)\) that refer to different particle configurations. Next, to obtain the particle trajectories for different initial configurations, numerical integration is done by interpolating \(\dot{h} = U_z, \dot{\theta} = -\Omega_x\), where \(\bar{h} = hR\), \(R\) being the particle radius. The calculations are carried out for \(h \geq 1.02\) to prevent any loss of any numerical accuracy. These trajectories gives us a better visualization of the particle dynamics and are represented in the form of the phase portraits, the particle configuration is shown in SI Fig. 10.

6 Acknowledgements

The authors thank MN Popescu for constructive discussions and help to select and evaluate the phase portraits. LN, LLW and JS acknowledge the Volkswagen foundation for the Freigeist fellowship (grant number 91619), as well as the Kaercher foundation for financial support.

References

[1] John L Anderson. Colloid transport by interfacial forces. *Annual review of fluid mechanics*, 21(1):61–99, 1989.

[2] JP Armitage. Bacterial tactic responses. *Advances in microbial physiology*, 41:229—289, 1999.

[3] Judith P. Armitage and Klaas J. Hellingwerf. Light-induced behavioral responses (‘phototaxis’) in prokaryotes. *Photosynthesis Research*, 76(1):145–155, Apr 2003.

[4] Larysa Baraban, Denys Makarov, Oliver G. Schmidt, Gianaurelio Cuniberti, Paul Leiderer, and Artur Erbe. Control over Janus micromotors by the strength of a magnetic field. *Nanoscale*, 5(4):1332–1336, 2013.

[5] Chuanrui Chen, Fangzhi Mou, Leilei Xu, Shaofei Wang, Jianguo Guan, Zunpeng Feng,
Quanwei Wang, Lei Kong, Wei Li, Joseph Wang, and Qingjie Zhang. Light-Steered Isotropic Semiconductor Micromotors. *Advanced Materials*, 29:1603374, 2017.

[6] Baohu Dai, Jizhuang Wang, Ze Xiong, Xiaojun Zhan, Wei Dai, Chien-Cheng Li, Shien-Ping Feng, and Jinyao Tang. Programmable artificial phototactic microswimmer. *Nature nanotechnology*, 11(12):1087, 2016.

[7] Renfeng Dong, Qilu Zhang, Wei Gao, Allen Pei, and Biye Ren. Highly efficient light-driven TiO2-Au Janus Micromotors. *ACS Nano*, 10(1):839–844, 2016.

[8] Stephen Ebbens, Mei-Hsien Tu, Jonathan R. Howse, and Ramin Golestanian. Size dependence of the propulsion velocity for catalytic janus-sphere swimmers. *Phys. Rev. E*, 85:020401, Feb 2012.

[9] Peer Fischer and Ambarish Ghosh. Magnetically actuated propulsion at low Reynolds numbers: Towards nanoscale control. *Nanoscale*, 3(2):557–563, 2011.

[10] Wouter D. Hoff, Michael A. van der Horst, Clara B. Nudel, and Klaas J. Hellingwerf. *Prokaryotic Phototaxis*, pages 25–49. Humana Press, Totowa, NJ, 2009.

[11] Bumjin Jang, Ayoung Hong, Ha Eun Kang, Carlos Alcantara, Samuel Charreyron, Fajer Mushtaq, Eva Pellicer, Robert Büchel, Jordi Sort, Sung Sik Lee, Bradley J. Nelson, and Salvador Pané. Multiwavelength Light-Responsive Au/B-TiO 2 Janus Micromotors. *ACS Nano*, 11(6):6146–6154, 2017.

[12] Gáspár Jékely. Evolution of phototaxis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1531):2795–2808, 2009.

[13] Sho Kaneko, Kouichi Asakura, and Taisuke Banno. Phototactic behavior of self-propelled micrometer-sized oil droplets in a surfactant solution. *Chem. Commun.*, 53:2237–2240, 2017.

[14] John O. Kessler, Aurora M. Nedelcu, Cristian A. Solari, and Deborah E. Shelton. *Cells*
Acting as Lenses: A Possible Role for Light in the Evolution of Morphological Asymmetry in Multicellular Volvocine Algae, pages 225–243. Springer Netherlands, Dordrecht, 2015.

[15] Islam S.M. Khalil, Veronika Magdanz, Samuel Sanchez, Oliver G. Schmidt, and Sarthak Misra. Precise localization and control of catalytic janus micromotors using weak magnetic fields. International Journal of Advanced Robotic Systems, 12:1–7, 2015.

[16] Minsu Kim. Phototaxis of cyanobacteria under complex light environments. mBio, 8(2), 2017.

[17] Federico Lancia, Takaki Yamamoto, Alexander Ryabchun, Tadatsugu Yamaguchi, Masaki Sano, and Nathalie Katsonis. Reorientation behavior in the helical motility of light-responsive spiral droplets. Nature communications, 10(1):1–8, 2019.

[18] Wei Li, Xiaoran Wu, Hong Qin, Zhongqiang Zhao, and Hewen Liu. Light-driven and light-guided microswimmers. Advanced Functional Materials, 26(18):3164–3171, 2016.

[19] Qing long Wang, Chun Wang, Renfeng Dong, Qi qi Pang, and Yuepeng Cai. Steerable light-driven TiO2-Fe Janus micromotor. Inorganic Chemistry Communications, 91:1–4, 2018.

[20] Celia Lozano, Borge Ten Hagen, Hartmut Löwen, and Clemens Bechinger. Phototaxis of synthetic microswimmers in optical landscapes. Nature communications, 7(1):1–10, 2016.

[21] Fangzhi Mou, Lei Kong, Chuanrui Chen, Zhihong Chen, Leilei Xu, and Jianguo Guan. Light-controlled propulsion, aggregation and separation of water-fuelled tio2/pt janus submicromotors and their “on-the-fly” photocatalytic activities. Nanoscale, 8:4976–4983, 2016.

[22] Gareth Roberts. ed. Langmuir-blodgett films. Springer Science & Business Media, 2013.

[23] Felix Ruhnow, David Zwicker, and Stefan Diez. Tracking single particles and elongated filaments with nanometer precision. Biophysical Journal, 100(11):2820–2828, 2011.
[24] Nils Schuergers, Tchern Lenn, Ronald Kampmann, Markus V Meissner, Tiago Esteves, Maja Temerinac-Ott, Jan G Korvink, Alan R Lowe, Conrad W Mullineaux, and Annegret Wilde. Cyanobacteria use micro-optics to sense light direction. *eLife*, 5:e12620, feb 2016.

[25] Shunsuke Tanaka, Daisuke Nogami, Natsuki Tsuda, and Yoshikazu Miyake. Synthesis of highly-monodisperse spherical titania particles with diameters in the submicron range. *Journal of Colloid and Interface Science*, 334(2):188–194, 2009.

[26] W. E. Uspal, M. N. Popescu, S. Dietrich, and M. Tasinkevych. Self-propulsion of a catalytically active particle near a planar wall: from reflection to sliding and hovering. *Soft Matter*, 11:434–438, 2015.

[27] P Varuni, Shakti N Menon, and Gautam I Menon. Phototaxis as a collective phenomenon in cyanobacterial colonies. *Scientific reports*, 7(1):1–10, 2017.

[28] George H Wadhams and Judith P Armitage. Making sense of it all: bacterial chemotaxis. *Nature reviews Molecular cell biology*, 5(12):1024–1037, 2004.

[29] Linlin Wang, Mihail N. Popescu, Fernando Stavale, Astrid Ali, Thomas Gemming, and Juliane Simmchen. Cu@TiO2 Janus microswimmers with a versatile motion mechanism. *Soft Matter*, 14(34):6969–6973, 2018.

[30] J Widoniak and G Maret. Synthesis and Characterization of Porous and Nonporous Monodisperse Colloidal TiO2 Particles. *Chem. Mater.*, (10):6–11, 2004.

[31] Annegret Wilde and Conrad W. Mullineaux. Light-controlled motility in prokaryotes and the problem of directional light perception. *FEMS Microbiology Reviews*, 41(6):900–922, 10 2017.

[32] Jing Yan, Sung Chul Bae, and Steve Granick. Colloidal superstructures programmed into magnetic janus particles. *Advanced Materials*, 27(5):874–879, 2015.

[33] Yiling Yang, Vinson Lam, Marie Adomako, Ryan Simkovsky, Annik Jakob, Nathan C. Rockwell, Susan E. Cohen, Arnaud Taton, Jingtong Wang, J. Clark Lagarias, Annegret
Wilde, David R. Nobles, Jerry J. Brand, and Susan S. Golden. Phototaxis in a wild isolate of the cyanobacterium synechococcus elongatus. *Proceedings of the National Academy of Sciences*, 115(52):E12378–E12387, 2018.

[34] Zhenrong Ye, Yunyu Sun, Hui Zhang, Bo Song, and Bin Dong. A phototactic micromotor based on platinum nanoparticle decorated carbon nitride. *Nanoscale*, 9:18516–18522, 2017.

[35] Nan Yu, Xin Lou, Ke Chen, and Mingcheng Yang. Phototaxis of active colloids by self-thermophoresis. *Soft Matter*, 15:408–414, 2019.

[36] Dongmei Zhang, Yunyu Sun, Mingtong Li, Hui Zhang, Bo Song, and Bin Dong. A phototactic liquid micromotor. *J. Mater. Chem. C*, 6:12234–12239, 2018.
Supporting Information Apparent phototaxis enabled by BM

February 2020

Figure 1: Results of powder XRD measurements of the 4 particle samples with average sizes of A 0.7 µm, B 1.2 µm, C 1.6 µm and D 3.5 µm. The coloured lines show, the typical XRD patterns of pure Anatase and Rutil phase taken from database.
Figure 2: A, schematical illustration of microscope apparatus with light paths of white light (yellow) and green + UV light in purple. B and C, pictures of self designed mountings for magnetic coils and cover glass on the microscope platform. C is equipped with a turnable disc for free adjustment of the magnetic field direction in plane. Both pictures show the typical alignment for vertical particle movement according to the figures in main text.

Figure 3: Fieldlines of magnetic coil setup with $\vec{B} = 5$ mT at different positions of cover glass. E yellow rectangle marks area with mostly homogeneous field, which was used for experimental operations.
Figure 4: Particle tracks with different orientations of magnetic field. B, fieldlines in 90° angle towards horizontal axis. D, fieldlines in 45° angle towards horizontal axis. A and C show, alignment of magnetic coils for experiments B and D.

Figure 5: Independence of particle behaviour towards thickness of Ni layer. A shows the typical velocities of 0.7 µm sized particles with different covering thicknesses of Ni. B, illustrates the tendency of the three samples in A to switch their movement direction according to vertical axis (y).
Figure 6: Tendency of turning back, depending on velocity for 0.7 µm particle under 2 different concentrations of hydrogen peroxide.

| Condition | Illustration | $\Phi$ [''] | $\Theta$ [''] | Motion |
|-----------|--------------|-------------|--------------|--------|
| No activity, no constraints through any external influences | | Not restricted | Not restricted | Brownian motion |
| No activity, magnetic field $B$ in $Y$ direction | Magnetic moment of the cap is aligned with $B$, $\Phi \parallel B$ | Not restricted | | Restricted Brownian motion |
| Activity without any external field | | | $\Theta = -\pi/2$, $\pi/2$ | Ballistic motion of random orientation |
| Activity in magnetic field | Fixed at $\Phi \parallel B$ | | $\Theta = -\pi/2$, $\pi/2$ | Ballistic motion directed by $B$ |

Figure 7: The magnetic field as well as the activity influence the orientation of the particle, all influences and the angles are detailed here.
Figure 8: The magnetic field creates a sinusoidal potential that becomes 0 only if the particle’s cap is aligned with B. This is the case for $\phi = n\pi$ meaning any rotation around the y axis maintaining the cap orientation parallel to B is allowed.

Figure 9: Light restricted by aperture. A visualized UV-light by fluorescent pyranin dye B visible green light without addition of UV fraction.

Figure 10: the particle configuration used for calculating phase portraits.
