

QUANTUM IS IN THE EYE OF THE BEHOLDER

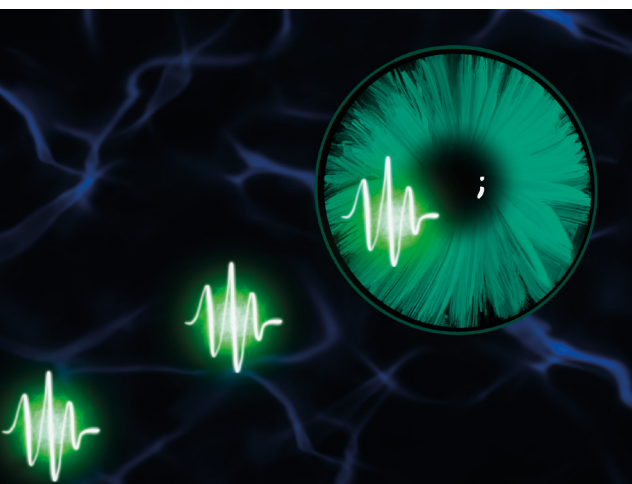
Gabriele BIZZARRI¹, Assunta DI VIZIO¹, Matteo ROSATI², Ilaria GIANANI¹, Marco BARBIERI^{1,3,*}

¹ Dipartimento di Scienze, Università degli Studi Roma Tre, Rome, Italy

² Dipartimento di Ingegneria Civile, Informatica e delle Tecnologie Aeronautiche, Università degli Studi Roma Tre, Rome, Italy

³ Istituto Nazionale di Ottica – CNR, Florence, Italy

* marco.barbieri@uniroma3.it



The evolving understanding of the limits of human visual perception has advanced the development of optical devices that not only correct visual defects but also help manage changes in certain eye structures. As modern optical technologies allow precise control of the quantum properties of light, recent endeavours have started testing the quantum capabilities of human eye perception, proving that they can detect single photons. This paves the way for the application of quantum metrology and cryptography to medical imaging, with potential increase in precision and security.

<https://doi.org/10.1051/photon/202513154>

Vision is the primary means for exploring the world. In the animal kingdom, we observe a variety of eye systems as different as the segment eye of insects, to the complex arrangements of some crustaceans [1]. In comparison, the human eye appears as a fairly simple system, with its three kinds of cones for colour vision, and its high density of receptors in the central fovea for spatial resolution. Yet, despite millennia of scrutiny, its structure and functions keep revealing unexpected subtleties. For instance, the peripheral retina is now held responsible for driving a

feedback mechanism for the axial eye growth. Based on this hypothesis, improved corrections of myopia in young individuals have been realised, slowing its progression [2].

This demonstrates how a deeper scientific understanding of the eye can have profound implications for health and well-being. This has been made possible, until now, by steady technological progress that has resulted in novel instruments for diagnostics and analysis. Thanks to the efforts invested in enhancing imaging tools, we can now depend on fundus cameras, corneal topographers, and ocular aberrometers, to name a few, for the benefit of eye health and visual

comfort. The current frontier in optical systems is beginning to expand its reach beyond issues in classical optics, exploring quantum aspects [3]. Advancements made in the last three decades now enable us to control light at the quantum level, including the ability to produce single photons with finely tuned spectral, temporal, and spatial properties.

These observations raise the question of whether quantum photonics can offer solutions for examining the eye, possibly down to the single photon level. We review results that establish this as a viable option, although with plenty of stimulating challenges ahead.

QUANTUM LIGHT AND THE EYE

Studies of the intensity threshold for human vision date back to the late 1800s, but fully reliable results were obtained much later, in the 1940s, through the pioneering work of Hecht *et al.* [4]. This research accounted for what the authors defined as “the best physical and physiological conditions.” By using filtered light, both in wavelength and intensity, and paying meticulous attention to the calibration of absorptions in the eye media and rhodopsin, the authors established that “to see, it is necessary for 1 quantum of light to be absorbed by 5 to 14 retinal rods” [4]. The technology available at that time did not allow for control over the photon number. Subsequent investigations demonstrated the capability of retinal cells to detect single photons, thanks to a combination of four factors highlighted in [5]: 1. high efficiency, 2. low noise, 3. significant amplification, and 4. reproducibility of the signal waveform.

The advent of quantum photonics now allows for the production of single photons with an excellent degree of approximation, and this has led to experiments conducted with superior control. In particular, Phan and coworkers reported in 2014 [6] that ex-vivo retinal cells from *Xenopus* toads could produce a detectable signal when illuminated with single photons at 532 nm – the reported value of the second-order correlation $g^{(2)}(0)=0.08$ corresponds to a multiphoton suppression by a factor 12 with respect to classical light of equivalent intensity. The signal from individual cells, collected by means of an electrode, confirmed the presence of those remarkable detection properties.

The mere presence of such a physiological capability does not imply that this is then actually used in the visual function. In fact, a complex arrangement of neural cells processes the signal emerging from the receptors before this is transmitted over the optical nerve, and then there is the active interpretation of the stimulus

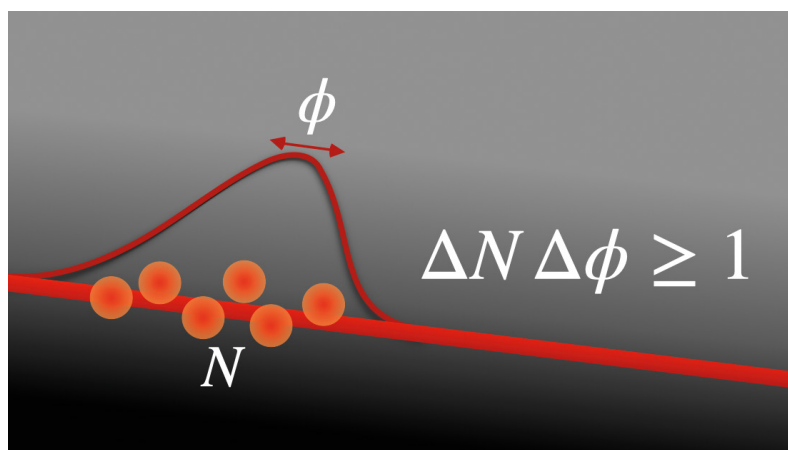
by the brain. The confirmation that humans can actually see single photons directly – i.e. that they can be perceived by the visual system – has been published in 2016 by Tinsley *et al.* [7]. The authors have asked subjects to give a yes/no answer upon the stimulation from a single-photon source and to rate their confidence in their response. The probability of seeing a photon was found to exceed the random guessing baseline ($p_{\text{see}} = 0.516 \pm 0.010$), reaching even higher significance for high-confidence events ($p_{\text{see}} = 0.60 \pm 0.03$).

Using sub-Poissonian statistics for investigating vision is an intriguing exploration, partly connected

to the question of whether and how quantumness is preserved in energy transduction in biosystems [8]. This however barely strokes the surface of the potential quantum photonics may hold for these investigations. There exists a much richer toolbox that can be put to good use. The eye can be considered as a quantum detector, thus its description can be elaborated in terms of detector tomography. This idea was first presented by van der Reep *et al.*, considering the domain of the intensity response [9]. They showed that, even taking in due consideration the limitations of subjective responses from psychophysical tests and the ●●●

QUANTUM CRYPTOGRAPHY AND QUANTUM METROLOGY

All quantum objects must satisfy Heisenberg’s relation $\Delta x \Delta p \geq \frac{\hbar}{2}$ accounting for how the uncertainty on the quantity x limits the one on the conjugated quantity p . Photons can thus be prepared in quantum states with enhanced precision for measurements with respect to classical light, by suppressing the intrinsic fluctuations in one quantity by increasing those of another: this applies to polarization, to orbital angular momentum and to phase ϕ and photon number N , using the proper units. This implies, for instance, that a beam with suppressed phase fluctuations would show increased fluctuations of its intensity, and vice versa. In addition, an eavesdropper attempting to read the value of x would be caught, since it necessarily produces an increase in Δp . By exploiting the opportunities granted by Heisenberg’s relation and turning its limitations to our advantage, it could be possible to combine precision and security in a single cryptographically protected scheme.



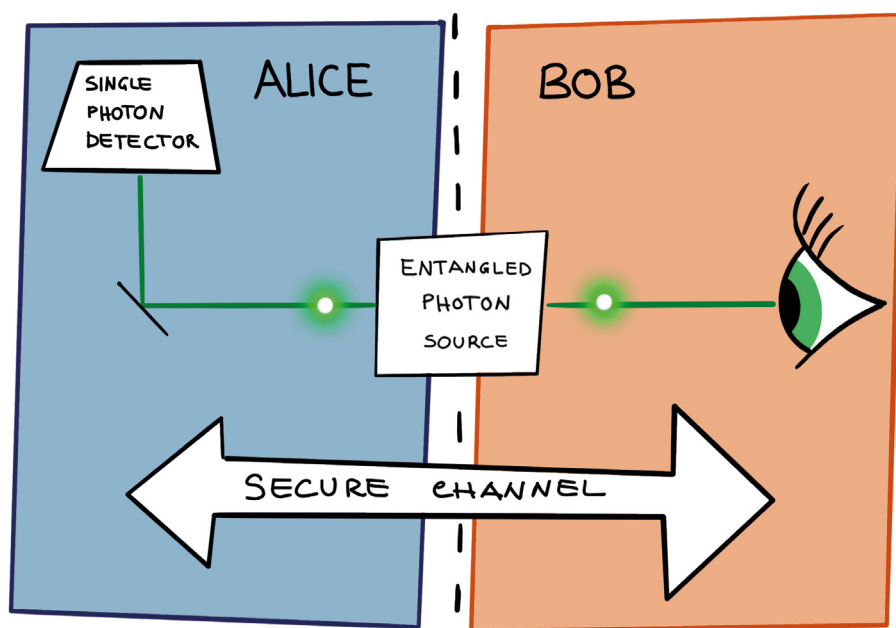
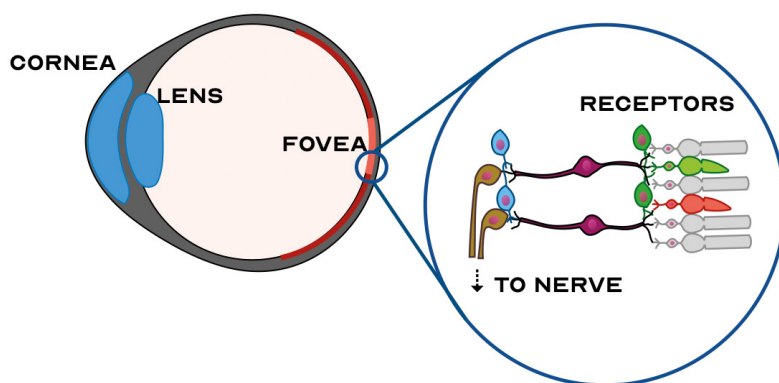


Figure 1. Quantum technologies may usher in a new way of performing measurements of the eye while ensuring secure transmission. Light controlled at its ultimate quantum level can be prepared in a state showing entanglement, i.e. a connection among its constituents beyond what is possible by purely classical means. These correlations can be so strong that, while the overall state is specified, each partition carries limited information. This is only retrieved when access is granted to the whole state. Measurement performed remotely by Alice on Bob's eye can thus be made secure by the use of entangled photons since verifying the integrity of their correlations provides a way to certify the integrity of the measurement itself using protocols of quantum cryptography. Light can thus serve as the means to observe and encrypt at the same time.

RETINA AS A DETECTOR

The eye can be considered as a detector with its entrance focussing elements (the cornea and the crystalline lens) and an active layer. This is composed of receptor cells containing rhodopsin or iodopsin molecules that undergo activation upon absorption of light by a phototransductive mechanism. This signal is conveyed to the brain via the optical nerve, but it passes first through a network of specialized neural cells. Different kinds of photoreceptors have a distinct spectral response and their density changes with the relative position to the central region of the fovea.



limited available time, an accurate reconstruction can be achieved. It could be interesting to extend those considerations also to the spatial domain, envisaging techniques to infer the spatial distribution of low-light sensitivity in individuals. Many ocular pathologies, especially those affecting the retina and the optical nerve, become manifest as alterations of vision with the appearance of blind spots. Typically, the disease at its onset exhibits a distinct spatial profile of the alteration. Tests at very low illumination levels that have access to the spatial resolution on the retina may uncover such pathologies at an earlier stage.

Loulakis and coworkers have introduced the intriguing idea of using quantum parameter estimation as a tool for biometric recognition [9]. Their original idea concerned the estimation of the transmissivity of the ocular medium as a marker based on “the photon-counting principles of human rod vision” [10]. This concept can also be extended to other ocular structures, such as the corneal surface or specific spatial characteristics of the pupillary frill and the optic nerve on the retina. Differently from the usual setting in quantum sensing, however, this valid proposal is faced with the challenge of taking into account the natural variability of those parameters. For instance, the opacity of the eye media is influenced by hydration. A good balance should be found between the required accuracy and precision demanded by biometry on the one side and the tolerance demanded by physiology.

The appeal of quantum light in such applications not only resides in its sensing power but also in the fact that it may become possible to combine the recognition protocol with secure data transmission. Controlling the quantum state of light is the key aspect that permits improved performance for precision measurement, but also what ensures security in quantum cryptography. Combining the two tasks in one system taking up

both roles is a challenge that is emerging as a novel direction for quantum technologies [11]. The system that can be envisioned may consist in a two-beam state exhibiting quantum entanglement, linking the subject Bob to an operator Alice carrying out a measurement remotely. This ensures that Alice, by only sending one half of the total state, gives out limited information to the external world, but her additional knowledge from the second half provides her with means for measuring.

The detailed design of the scheme will demand addressing several trade-off conditions. The first concerns the quantum state itself that will need to be able to measure accurately and precisely as well as to protect the available information by revealing intrusions. A fine balance in its quantum properties should be met for the state to remain robust against imperfections such as loss and, at the same time, testable for security. The second aspect is related to the fact that data transmission typically uses infrared wavelengths, but these have limited applicability to measurements of the retina. This may require sophisticated photonics solutions for the realisation of efficient frequency converters.

CONCLUSION

Quantum metrology and cryptography are among the most promising quantum technologies to date, having led already to practical demonstrations and technological applications. Recent investigations into the single-photon detection capabilities of the human eye pave the way for wider usage of quantum-mechanical features in such systems while at the same time calling for considerable steps forward to balance traditional performance measures with medical safety. In taking up this challenge, it will be crucial not to forget

the lesson that the best physical and physiological conditions should be met, and genuine progress would only emerge from collaborative, multidisciplinary efforts.

This new frontier of quantum-assisted medical imaging might advance both our fundamental understanding of human vision and our diagnostic capabilities, thanks to the use of lower-intensity signals achieving higher measurement precision and enabling the acquisition of medical data with privacy guaranteed by quantum-mechanical laws. ●

REFERENCES

- [1] S. Kleinlogel, and A.G. White, *PLoS ONE* **3**: e2190 (2008)
- [2] A. Russo, A. Boldini, D. Romano *et al.*, *J. Ophthalmol.* **2022**, 1004977 (2022)
- [3] E. Polino, M. Valeri, N. Spagnolo, and F. Sciarrino, *AVS Quantum Sci.* **2**, 024703 (2020)
- [4] S. Hecht, S. Shlaer, and M. H. Pirenne, *J. Gen. Physiol.* **25**, 819 (1942)
- [5] F. Rieke and D. A. Baylor, *Rev. Mod. Phys.* **70**, 1027 (1998)
- [6] N.M. Phan, M.F. Cheng, D.A. Bessarab, and L.A. Krivitsky *Phys. Rev. Lett.* **112**, 213601 (2014)
- [7] J.N. Tinsely, M.I. Molodtsov, R. Prevedel, *et al.*, *Nat. Commun.* **7**, 12172 (2016)
- [8] Q. Li, K. Orcutt, R.L. Cook, *et al.*, *Nature* **619**, 300-304 (2023)
- [9] T. H. A. van der Reep, D. Molenaar, W. Löffler, and Y. Pinto, *J. Opt. Soc. Am. A* **40**, 285 (2023)
- [10] M. Loulakis, G. Blatsios, C. S. Vrettou, and I. K. Komninos, *Phys. Rev. Res.* **8**, 044012 (2017)
- [11] Z. Huang, C. Macchiavella, and L. Maccone, *Phys. Rev. A* **99**, 022314 (2019)



Rock Solid
Zero offset frequency combs

 **TOPTICA**

