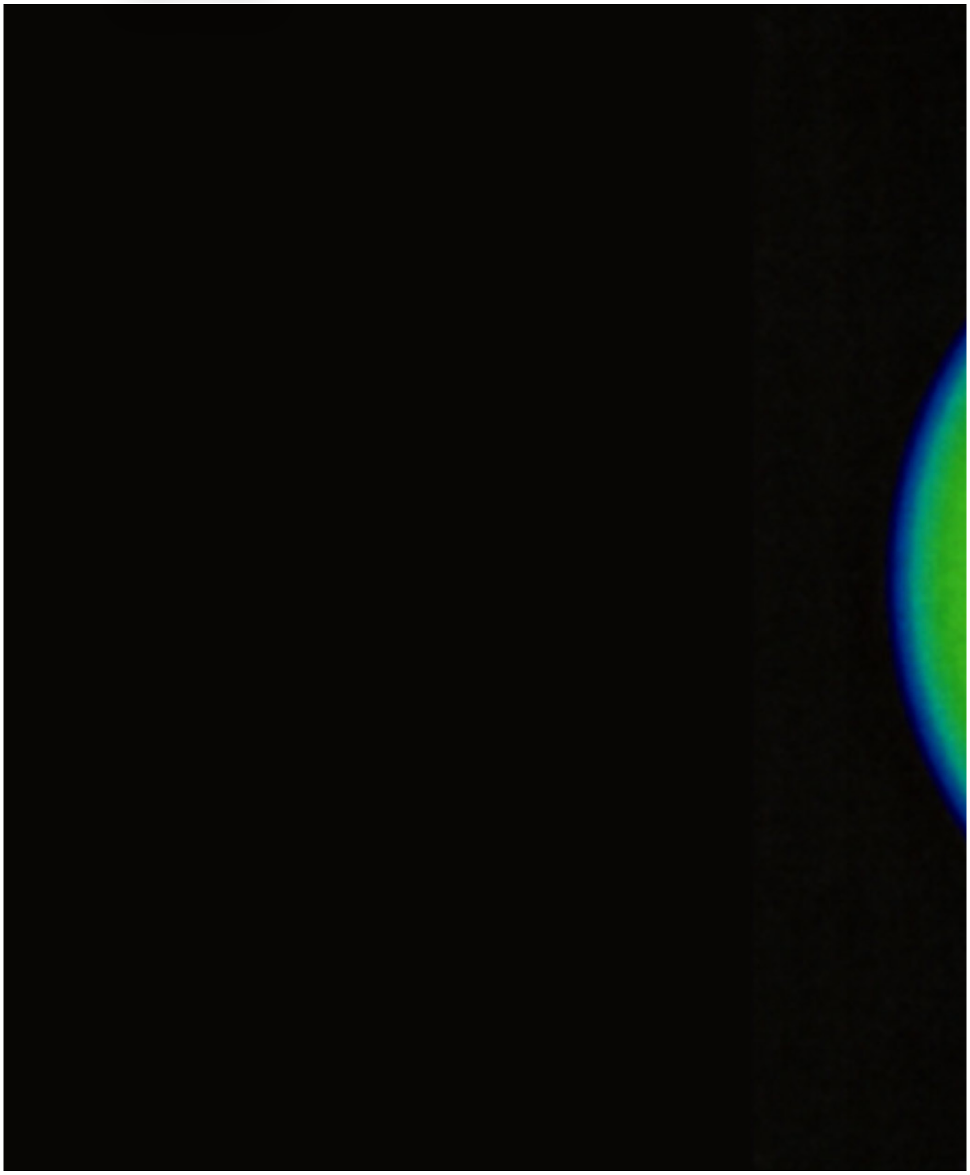

Seeing the quantum

The human eye is a surprisingly good phot
spy of the line between the quantum and c

Rebecca Holmes

I spent a lot of time in the dark in graduate school. Not just because I was learn
we usually deal with one particle of light or *photon* at a time – but because my r
measurement tool. I was studying how humans perceive the smallest amounts c

every time.

I conducted these experiments in a closet-sized room on the eighth floor of the of Illinois, working alongside my graduate advisor, Paul Kwiat, and psychologis equipped with special blackout curtains and a sealed door to achieve total dark hours in that room, sitting in an uncomfortable chair with my head supported i crosshairs, and waiting for tiny flashes delivered by the most precise light sourc My goal was to quantify <https://www.sciencedirect.com/science/article/pii/S I (and other volunteer observers) perceived flashes of light from a few hundred

As individual particles of light, photons belong to the world of quantum mecha the Universe we know. Physics professors tell students with a straight face that (*quantum superposition* <https://aeon.co/videos/the-physics-revolution-that-sta that a measurement on one photon can instantly affect another, far-away photo *entanglement* <https://aeon.co/ideas/you-thought-quantum-mechanics-was-we we accept these incredible ideas so casually because we usually don't have to in electron can be in two places at once; a soccer ball cannot.

But photons are quantum particles that human beings can, in fact, directly perc could force the quantum world to become visible, and we don't have to wait arc today's technology. The eye is a unique biological measurement device, and de research where we truly don't know what we might find. Studying what we see state could contribute to our understanding of the boundary between the quan observer might even participate in a test of the strangest consequences of quan

The human visual system works surprisingly well as a quantum detector. It's eyeball to the brain, that turns light into the images we perceive. Humans primary types of living light detectors: rod cells and cone cells. These photorece light-sensitive layer at the back of the eyeball. The cone cells provide colour visi well. The rod cells see only in black-and-white, but they are tuned for night visio about half an hour in darkness.

Rod cells are so sensitive that they can be activated by a single photon. One ph electron-volts of energy. (Even a flying mosquito has tens of *billions* of electron- chain reaction and feedback loop inside the rod cell amplifies this tiny signal in language of the neurons.

We know that rods are single-photon detectors because the electrical response measured in the lab. What remained unknown until recently was whether these of the visual system and cause an observer to see anything, or whether they're f was a difficult question to answer because the right tools didn't exist. The light neon lights is a random stream of photons, like raindrops falling from the sky. the next photon will come, or exactly how many photons will arrive in any time this fact makes it impossible to be sure that a human observer is really seeing j or three instead.

There are now two possible experiments that could b
the realm of human perception

Over the past 75 years or so, researchers have come up with clever ways to try t
problem. But in the late 1980s, a new field called quantum optics developed a r
source. This was a new kind of light that the world had never seen before, and i
exactly one photon at a time. Instead of a rainstorm, we now had an eyedroppe

Today there are many recipes for making single photons, including trapped ato
diamond crystals. My favourite recipe, which I learned as a graduate student, is
downconversion. Step one: take a laser and shine it on a beta-barium borate crys
sometimes spontaneously split apart into two daughter photons. The newborn
other end of the crystal, making a Y shape. Step two: take one of these daughte
detector, which 'clicks' whenever it detects a photon. Because the daughters ar
announces that exactly one photon is now present on the other side of the Y, re

There's one more important trick to studying single-photon vision. Just sending
asking: 'Did you see it?' is a flawed experimental design, because humans find t
objectively. We don't like to say 'yes' unless we're sure, but it's hard to be sure a
visual system – which can produce phantom flashes even in total darkness – al
strategy is to ask the observer to choose between two alternatives. In our exper
send a photon to the left or the right side of the observer's eye, and in each trial
observer can answer that question better than random guessing (which would
know they are seeing something. This is called a forced-choice experimental de
experiments.

In 2016, a Vienna-based research group led by the physicist Alipasha Vaziri fro
used a similar experiment to show <https://www.cell.com/cell/fulltext/S0092-
observers were able to respond to a forced choice with single photons better th
evidence so far that humans really can see just one photon. Using a single-phot
parametric downconversion, and a forced-choice experimental design, there ar
could bring quantum weirdness into the realm of human perception: a test usi
known as a 'Bell test' of non-locality using a human observer.

Superposition is a uniquely quantum concept. Quantum particles such as p
that a future measurement will find them in a particular location – so, befo
they can be in two (or more!) places at once. This idea applies not just to partic
such as polarisation, which refers to the orientation of the plane along which th
Measurement seems to make particles 'collapse' to one outcome or another, bu
collapse happens.

The human visual system provides interesting new ways to investigate this prob
be to determine whether humans perceive a difference between a photon in a s
definite location. Physicists have been interested in this question for years, and
for the moment let's consider the single-photon source described above, delive

right of an observer's eye.

First, we can deliver a photon in a superposition of the left and right positions –
an observer to report which side they believe the photon appeared on. To quan
between a superposition state and a random guess of left or right, the experime
trials in which the photon really is just sent either to the left or the right.

Creating the superposition state is the easy part. We can split the photon into a
positions using a polarising beam splitter, an optical component that both trans
polarisation. (Many surfaces do this – even ordinary window glass both transm
both the outdoors and your own reflection. Beam splitters are engineered to do
of transmission and reflection.)

Standard quantum mechanics predicts that a superposition of left and right sh
than a photon that's randomly sent either to the left or to the right. Upon reach
right will probably collapse to one side or the other so fast that it would be unn
experiment, so we don't know for sure. Any statistically significant difference i
something to the left or right in a superposition trial would be unexpected – an
quantum mechanics as we know it. The observer could also be asked to record
superposition state, compared with the random mixture. Again, according to st
expect to see any difference – but if we did, it could point to new physics and a
measurement problem.

> If humans can see single photons, an observer can pla
> realism

Human observers could also participate in a test of the other defining concept
Entangled particles share a quantum state, and behave as if they are joined tog
separated.

Bell tests, named for the Northern Irish physicist John S Bell, are a category of
entanglement violates some of our natural ideas about reality. In a Bell test, mea
particles show results that can't be explained by any theory that obeys the prin
pair of seemingly obvious assumptions. First is locality: things that are far apart
signal could travel between them (and the theory of relativity tells us that the sp
realism: things in the physical world have definite properties at all times, even i
with anything else.

The concept of a Bell test is that two particles interact with each other and beco
and make measurements for each one. We take at least two kinds of measurem
two different directions – and we decide which ones to make at random, so the
outcomes ahead of time. (This might sound like a bizarre conspiracy theory, bu
experimental consequences of entanglement, it's important to rule out every al
repeated many times with new pairs of particles to build up a statistical result. I
limit on how much the results between two particles should be correlated if the

In dozens of Bell tests, the limit has been broken, proving that quantum mecha
or both.

Entangled photons are usually the particle of choice for Bell tests, and the local-
made using electronic single-photon detectors. But if humans can see single ph
these detectors, playing a direct role in a test of local realism.

Conveniently, spontaneous parametric downconversion can also be used to pro
kind of experiment could use pairs of photons entangled in their polarisation. T
one photon goes to the observer when a certain outcome of a certain type of po
other measurements will be made by single-photon detectors, at least in a first e
take note of how often that measurement outcome occurs, and the number the
correlation calculation that measures whether or not local realism has been viol

But the observer will likely only be lucky enough to notice their photon in a sma
so they would never measure the true frequency of that measurement outcome
experiment will be carefully designed to eliminate bias and help the observer b
design is the secret ingredient again. We will randomly choose whether to send
side of the observer's eye, and at the same time send a second, non-entangled c
probability equal to the maximum expected frequency of the measurement out
In each trial, the observer will decide whether they saw anything on the left side
left, right, or both. If the observer chooses the side with the entangled photon a
choose the control side, the outcome violates local realism.

Why do these experiments? Beyond the 'far out' factor, there are serious s
superposition states collapse to definite outcomes is still one of the grea
quantum mechanics with a new, unique, ready-to-hand measurement apparatu
out or provide evidence for certain theories. In particular, a class of theories call
undiscovered physical process that always causes the superposition states of la
collapse very quickly. This would mean that large superpositions are actually im
disturbances from interactions with the environment. The Nobel prizewinning
University of Illinois has been pushing for experimental tests of such theories. I
experiments using the human visual system showed a clear divergence from st
evidence that something like macrorealism is at work.

Bell tests are also still an active area of research. In 2015, all the major Bell-test
that could have allowed local realism to persist, however unlikely – were finally
proposing and carrying out a variety of more exotic Bell tests, trying to push th
In 2017, researchers led by David Kaiser of the Massachusetts Institute of Tech
University of Vienna performed <https://arxiv.org/abs/1808.05966> a 'cosmic
stars to trigger the measurement settings, in an attempt to prove that predeterm
particles (which could open a loophole for local realism to persist) would have t
An international collaboration called the BIG Bell Test used random choices fro
participants to decide <https://www.nature.com/articles/s41586-018-0085-3>
in 2016. A Bell test with a human observer would be a fascinating addition to th

These days, I spend less time in blackened rooms than I once did. At Los Alamo
work on ways to use single photons (detected by electronics, not the eye) to cre
orbit around the Earth. But when this next generation of experiments makes qu
retreat back into the dark and fire up my own single-photon detectors again.

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in Physics World and Applied Optics, among others.*