Guest Editorial

PERCEPTION

To Bayes or not to Bayes . . .

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If you consider "Bayesianism" to be a theory of perception, you're not alone (Knill & Richards, 1996). Vision research has greatly boosted the Reverend Bayes' citation score (Bayes & Price, 1763). Bayesianism is generally appreciated in the sciences. Physicists tend to stick to "frequentism." Indeed, I consider frequentism mainly applicable in statistical mechanics—and casinos, of course.

What is the probability that a tossed coin will land head up? An *empirical physicist* will toss it a hundred times and count, then accept the frequency of head up as the probability. For good measure, this may be repeated 10 times (say), yielding different probabilities. The final answer might be the following: "probability of heads up is 0.51 ± 0.02" (results from an actual experiment performed by me). A *theoretical physicist* will reason from symmetry arguments and invoke the *Principle of Indifference* to arrive at an *exact* probability of 0.5, considering it the limit of the empirical physicist's outcome "for an infinite number of trials." Both physicists would agree that such a limit is a convenient fiction and that ideally "fair" coins do not exist. Both would consider subjective probabilities nonsense and even non-scientific because they are *observer dependent*. Bayes makes no sense to either of them.

Bayes makes such good sense in real life because it suggests *what to do next*. The needs of life are coping with the present and scheming for the future, taking cues from the past. Bayes seems indeed the perfect tool to handle that. Here I intend to sow some doubts.

Bayesianism adopts—and extends—the *formalism* of probability theory, but *conceptually*, it is in another ballpark. Bayesians and frequentists endlessly fight over roots. Probability theory has vague origins (Hacking, 2006). It seems confusing and even incoherent if you read up on the roots. But, fortunately, science has arrived at a coherent formalism of arcane beauty. History is left to the historians.

Probability theory with the Bayesian twist has amazingly wide applicability—that's why I appreciate it. Consider Cox's theorem (Cox, 1946), or the efforts of Jaynes. Jaynes' posthumous book (Jaynes, 2003) carries the subtitle "The Logic of Science." Such is the essential import of Cox's theorem. A few apparently obvious assumptions suffice to show that probability calculus is the only game in town and should replace classical logic in real life. This holds true for the sciences, so Jaynes' subtitle applies. I'm really annoyed that my friends in theoretical physics—all hardcore frequentists—fail to appreciate that.

If Bayesianism is indeed the "Logic of Science," then might it be the "Logic of Perception," or even the "Logic of Life" as well? If you think so, then count yourself among the Bayesians of vision science. This is pretty much the mainstream conviction, so you're in the best of company!

However, theories about "what to do next" or "how to bet" cannot be mere *formalisms*. The roots dig deep into what the theory *is about*. That is to say, the formalism may be a beautiful edifice, maintained by formalists who take no part in life's affairs, but it is constructed on foundations that dig deep down into the blood and bones of the matter.

My major interest is *life*. Biological agents are thrown into the world and have to cope with what meets them, or what they encounter when nosing around. What might their Bayesian priors be? There cannot be *any* answer to that. People say "*anything could happen*, so the obvious prior is equal weight on *everything*." True enough! Unfortunately, "equal weight" is ill defined, but perhaps Jaynes' theory of "transformation groups" handles that technicality. Does it make sense then? Not to me. Priors apply to known domains, but organisms lack a panoramic view of possible events. *Anything* might conceivably happen! Anyplace, anytime, without "sufficient reason." Suppose you've "seen it all." The next moment your world might conceivably jump into a new mode, it is not for you—nor for science—to decide. *Probabilistic reasoning has no handle*, for you cannot assign a prior on a universe that *you do not and cannot know*. There exists a categorical difference between the merely unknown and the unknowable (Gomory, 1995). You can reason about the unknown but not about the unknowable. One can only drink to that.

Probability theory is firmly rooted in the Belief in the All Seeing Eye (Koenderink, 2014). Probabilities apply to entities for which *there exists a fact of the matter*. Although the facts of the matter are hidden, Cox's theorem presumes that the facts are *real* nevertheless. If not seen by you, then at least they are visible to the All Seeing Eye. This applies in classical physics, so Jaynes could base his Bayesian "logic of science" on classical logic. But *the organism thrown into the world is left out in the cold*. Will it bet its life on the Law of the Excluded Middle (Aristotle, 350 BCE; Brouwer, 1923)? Would *you* when the rubber hits the road? Classical logic simply fails to apply to life's problems.

Suppose a friend tosses a coin and puts a hand over it, merely stating that "head did not come up." Does this imply that tail came up? If you think so, you applied the *Law of the Excluded Middle*. This implies that you silently excluded numerous alternatives. The coin may *mirabile dictu* have landed on its edge, it may have shattered on impact, your friend may have tossed an unfair coin with two tails and so forth *ad infinitum*. You are a believer. Does that mean you were stupid? No, but only that your conclusion was *not a logical one*. Logic proper doesn't apply to life.

Probability theory deals with "epistemic uncertainty," that is *insufficient data on determinate facts*. But is doesn't deal with vagueness, with ambiguity, or with events that come out of the blue. But, as they say, *shit happens*. The dinosaurs were not prepared for that, and we all know what happened to them. Are we in a better position ourselves? Bayes will not come to the rescue. NASA is trying hard to make us do better than the dinosaurs, at least on the asteroid issue (the "Asteroid Redirect Mission"). But are comets our major problem? We do not *and cannot* know.

All organisms can do to deal with the unknowable is to hope for the best and hunt for lasting structure, that has *repetition* over time or space. Especially, coincidences of rare events might prove important. You only die once! The myriads of common repeats are important too, but these are handled automatically by your body. You'll never notice. Remember water is tasteless because you were born with it in your mouth? Something recurring *once* should be noticed, *another* occurrence should be noted as a regularity, *a third time* perhaps as a "Law of Nature." Equally important, if such recurrences do not continue to occur, your interest should dwindle. That is how "affordances" come and go. It does not require much of a logical calculus for its implementation (Riedl, 1980). It is how evolution creates a "ratiomorphic apparatus" (Brunswick, 1952).

The possibilities that an organism may reckon with are necessarily part of its *Umwelt*. That involves its *Merkwelt* ("sense world"), comprising any physical events that reliably affect its awareness, as well as its *Wirkwelt* ("action world"), comprising the repertoire of its possible actions. I'm referring to Jakob von Uexküll (1909, 1920) and von Uexküll and Kriszat (1934)

here, hence the German terms. The Bayesian priors apply to the *Umwelt*, not to the physical environment.

Bayesian inferences apply to expectations following potential actions, not to physical events. That is the crux of the matter. It renders Baysesian inference at least *possible* because it takes the All Seeing Eye out of the equation. It defines the domain over which priors can sensibly be assigned. I have rarely seen that acknowledged, with the exception of Hoffman and Prakash (2014).

Bayes indeed applies to events that are possible in the organism's Umwelt, but not to *any* events that might happen in the "physical world." The latter notion remains undefined. Just consider whether you should include physics that still has to be discovered? Is that part of your "physical world?" Of any animal's? The dinosaurs could not have reckoned with comets because these were not part of their Umwelts. Newton could not reckon with the Higgs boson (Higgs, 2013).

But, perhaps sadly, this "solution" implies that Bayesianism yields no handle on perception, because *it presumes a knowledge of perception*—the structure of the Umwelt—before it can be wielded at all (at least implicit in van der Helm, 2011).

That sounds like the end of an interesting idea. At least to me. On a more positive note, it might become the start of another one.

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Editorial note

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