A Consciousness Meter

An electromagnetic gadget to measure the level of consciousness

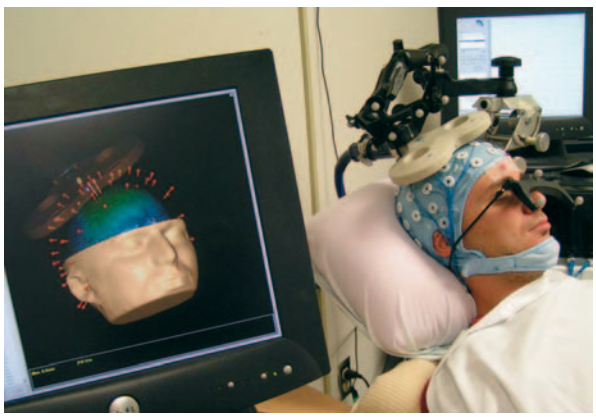
BY CHRISTOF KOCH

Measure what is measurable, and make measurable what is not so.

THIS QUOTE FROM Galileo Galilei, one of the founding fathers of science, is a call to arms for ingenious bench scientists, clinicians and theoreticians to render consciousness measurable: to build an instrument that can tell whether that prone person who is nonresponsive or behaving in a reflexlike manner is actually conscious of something—of anything. Such a "consciousness meter" should reliably distinguish between a sleeper who is experiencing a vivid dream—even if she does not recall most of its content later on—and one who is in a dreamless, deep sleep, not feeling anything. Not just black but nothing, *nichts, nada, rien*. Or between a patient who is deeply anesthetized, and oblivious to the abdominal surgery being performed on him, and the rare cases of "awareness under anesthesia." Such a device should also be able to tell whether a grievously brain-injured patient, whose electroencephalograph (EEG) might be flat but who is moaning and occasionally moving his head or limbs, is experiencing pain or distress or is truly not conscious—alive but oblivious to the world.

Most scholars of consciousness aver that to be aware of something is to have a single, integrated experience. When looking at a sunset, for instance, you cannot separate the garish purple-orange hues from the bright globe about to sink below the horizon. Unless you are colorblind, color is a holistic aspect of your experience. When you are looking out at the world, you cannot make yourself be only conscious of the left or the right half of your visual field. You experience both. Whatever information you are conscious of is wholly and completely presented to your mind; it cannot be subdivided.

Underlying this unity of consciousness is a multitude of causal interactions among the relevant parts of the brain that create the mind. If areas of the brain start to disconnect or become fragmented and balkanized, as occurs in deep sleep or in anesthesia, consciousness fades and might cease altogether. Giulio Tononi, a neuroscientist, psychiatrist and expert on sleep and consciousness at the University of Wisconsin–Madison, has made this phenomenal aspect of consciousness the centerpiece of his Integrated Information Theory of consciousness [see "A 'Complex' Theory of Consciousness," Consciousness Redux; July/August 2009].



To assess the level of consciousness, a coil-like electromagnetic device (*shown above the head*) applies a pulse; the brain's responses are recorded via EEG electrodes.

Tononi, together with his colleague Marcello Massimini, now a professor at the University of Milan, Italy, and a few others set out to measure the extent to which the brain is integrated during sleep and during various pathological states.

The Bell of Consciousness

In a series of experiments, the researchers delivered a single, high-field pulse of magnetic energy via a technique called transcranial magnetic stimulation (TMS) to the heads of volunteers. Discharging a plastic-enclosed coil of wire held against the scalp induces a brief electric current in the gray matter underneath the skull (the subject feels a slight sting from stimulation of the skin). This pulse excites brain cells and nearby fibers of passage that will, in turn, engage synaptically connected neurons in a cascade of activity that reverberates inside the head.This electrical activity quickly dies out.

Tononi and Massimini rigged the subjects' scalp with 64 electrodes for recording the EEG while subjects were either quietly resting or asleep. When awake, the volunteers' EEG following the TMS pulse showed a typical waxing and waning pattern of fast, recurrent brain waves, lasting a third of a second or so. A mathematical analysis of the EEG signals revealed that a hotspot of high-amplitude potential traveled from the premotor cortex, above which the TMS coil was positioned, to the matching premotor cortex in the other hemisphere, to the motor cortex and to the posterior parietal cortices in the back. Think of the brain as a large church bell and the TMS device as the clapper. Once struck, a well-cast bell will ring at its characteristic pitch for a considerable time. And so does the awake cortex, buzzing between 10 to 40 times a second.

In contrast, the brain of a deep sleeper acts like a stunted, badly tuned bell. Whereas the initial amplitude of the EEG is larger than when a subject is awake, its duration is much shorter, and it does not reverberate across the cortex to other connected regions. Although the neurons remain active in sleep, as evidenced by the strong, local response, integration has broken down. Little of the spatially differentiated and temporally variegated

CHRISTOF KOCH (*Koch*); COURTESY OF MARCELLO MASSIMINI *University of Milan (apparatus and patient)*

sequence of electrical activity that is typical for the awake brain is present. The same is also true of subjects who volunteered to undergo general anesthesia with propofol or xenon. The TMS pulse invariably produces a simple response that remains local, indicative of a breakdown of cortico-cortical interactions and a lessening of integration.

drawn out over hopeless decades in hospices and nursing homes, is mirrored and amplified by the love—and the resources—her family expends on her care, always hoping for a miraculous recovery.

You may recall Terri Schiavo in Florida, who lingered for 15 years in a persistent vegetative state until her medically induced death in 2005. Because of the nasty, public fight between her husband, who advocated discontinuing life support, and her parents, who believed that their daughter had some measure of awareness, the case was litigated up and down the judicial chain, and eventually drew in then president George W. Bush. Medically, her case was uncontroversial. She had brief episodes of automatisms: head turning, eye movements and the like, but no reproducible or consistent, purposeful behavior. Her EEG was flat, indicating that her cerebral cortex had shut down. Her condition failed to improve over many years. The autopsy showed that her cortex had shrunk by half, with her visual centers atrophied; thus, contrary to public reports at the time, she could not have seen anything.

versity Hospital in Liège, Belgium, Massimini, Tononi and their colleagues measured the span of brain integration in such patients. They applied TMS pulses to the parietal or frontal lobes of patients who had their eyes open. The result was unambiguous. Patients in a vegetative state had simple and local EEG responses—usually a slow, single positive-negative wave (when they had any response at all)—resembling the deep sleep and anesthesia response. Contrariwise, in minimally conscious patients, the magnetic pulse triggered the complex electrical responses expected of healthy, awake subjects. Five patients were additionally recruited from intensive care as soon as they awoke from coma. Three eventually recovered awareness, and two did not.

> Think of the brain as **a large church bell** and the transcranial magnetic stimulation device as the clapper.

Probing the Mind of a Patient

When severe injury strikes the brain, consciousness may not return. A car accident, a fall, a combat wound, a drug or alcohol overdose, a near drowning—any of these can lead to profound unconsciousness. Thanks to rescue helicopters and emergency medical technicians, who quickly deliver the victim to the care of a team of specialized trauma nurses and physicians, many patients can be plucked back from the edge of death. Although this is a blessing for most, it is a curse for a few. They remain alive for years, never recovering consciousness, undead.

Impaired states of consciousness include coma, the vegetative state and the minimally conscious state. Overall arousal fluctuates from complete absence in coma, to periodic sleep-wake transitions in the vegetative state, to conscious awakenings with purposeful movements in the minimally conscious state, to more or less continual awareness.

In the U.S. alone, as many as 25,000 patients hover for years in a persistent vegetative state. What makes the situation almost unbearable is that they can look and act as if they are fully present. Indeed, such patients have daily sleep-wake cycles. When they are "awake," their eyes are open and they may move reflexively; they may grimace, turn their head, groan. To the naive observer, these movements and sounds suggest that the patient is awake, trying to communicate with loved ones. The tragedy of the ruined patient's blank and empty life,

In contrast to Schiavo, minimally conscious patients have fluctuating signs of nonreflexive reactions, such as pursuing a target with their eyes or making verbal or hand responses to simple commands. Whereas consciousness has fled patients in a vegetative state, it is partially preserved in minimally conscious ones. It is, of course, absolutely critical to tell the difference between one and the other. Yet this is often not possible with purely behavioral-based measures.

Neurologist Steven Laureys of Uni-

The onset of consciousness in those patients who did recover was preceded by a lengthening and complexification of the EEG response to the magnetic pulses—they progressed from a single localized wave to a much richer spatio-temporal pattern. In other words, this method can act as a crude consciousness meter. A miniaturized TMS coil in combination with an EEG device with a handful of electrodes can easily be assembled into an instrument.

In this way, theoretical insights into consciousness are married to clinical practice that benefits many. **M**

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(Further Reading)

- **Breakdown of Cortical Effective Connectivity during Sleep.** M. Massimini et al. in *Science,* Vol. 309, pages 2228–2232; September 30, 2005.
- **Recovery of Cortical Effective Connectivity and Recovery of Consciousness in Vegetative Patients.** M. Rosanova et al. in *Brain,* Vol. 135, No. 4; pages 1308–1320; 2012.