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Some historical crossroads between astronomy and visual neuroscience.

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Abstract. The histories of astronomy and visual neuroscience share some important events. Observation of the sky provided early basic information about visual acuity and sensitivity to light and their variations at different retinal locations. Some of the early tests of visual functions were inspired by astronomical knowledge existing since antiquity and possibly since human prehistory. After science became a hallmark of human civilization, astronomy played a crucial part in the discovery of the laws of nature. At the turn of the 19th century, astronomers discovered interindividual variability in detecting the time of stellar transit and tried to measure the so-called personal equation, a supposedly inherent individual bias in making observations, judgements and measurements. Convinced that the reliability of scientific observations depended on the reliability of the observer, they were the first scientists to realize that studying man and human psychophysiology was essential for achieving accuracy and objectivity in astronomy and other sciences alike. There is general consensus that the science of experimental psychology grew out of astronomy and physiology in connection with the development of the reaction time method and the so-called mental chronometry. The crucial role of the observer in astronomical observations appears to have been neglected by astronomers in the second half of the 19th century after Giovanni Schiaparelli described "canals" on the surface of the planet Mars. Percival Lowell and others thought that these canals had been constructed by a Martian intelligent population in order to distribute water from the polar regions to the equatorial deserts on the planet. Since it has been ascertained that the Mars canals seen by Schiaparelli do not exist, some speculations are offered from a neuroscientific viewpoint as to why he and others were mistaken in their observations of Mars.

Key words. Astronomy - Visual neuroscience - Personal equation - Schiaparelli - Mars canals

1. Introduction

There are many cultural and practical relationships between the history of astronomy and that of visual psychophysiology. Seeing, either by naked eye or through telescopes, is a staple ingredient of both amateur and professional astronomy. Indeed, for contemporary astronomy "seeing" is a measure of the stillness and clarity of Earth's atmosphere. In turn, contemporary neuroscience distinguishes seeing for action, that is for an immediate guidance of behaviour not necessarily associated with consciousness, and seeing for conscious awareness, that is for acquiring knowledge useful for future plans of action (Milner & Goodale 1996).

Seeing for action, which allows us to deal with earthly objects, is subject to the rule of size constancy: the size of seen objects is perceived as unchanging regardless of their distance, and regardless of the size of the image that they cast on the retina of the observer. Our visual interaction with celestial bodies is different because we have no direct way to estimate their actual size and their actual distance from us. The sun and the moon look of similar size to us because their retinal images subtend a similar visual angle (about half a degree), but the sun is much bigger and much farther from us than the moon. Both of them appear larger near the horizon than when they are high in the sky, but photographs taken at different elevations show that there is no actual change in size. One possible explanation of this illusory phenomenon combines the Ponzo illusion, whereby we attribute a relatively greater size to objects which appear more distant from us, and the general impression that the horizon is farther from us than the vault of the sky (Jones & Wilson 2009).

Nevertheless observation of the sky has long supplied humankind with vital information for the solution of practical problems on Earth. Probably already in human prehistory, crude measures of time and the planning of the calendar of early agricultural activities were based on the apparent movement and distance of the sun, and constellations were used by the first seamen as a compass for dead reckoning. Much later, after science became a hallmark of human civilization, astronomy played a crucial part in the discovery of the laws of nature. When in 1603 Federico Cesi founded the Accademia dei Lincei, soon thereafter joined by Galileo, astronomy figured prominently among the study objects which the academicians intended to pursue. They adopted an image of a lynx as the emblem of the Academy and called themselves Lincei, meaning to employ in their dispassionate observation of Nature an eyesight as sharp as that of the lynx, along with an even greater sagacity. Since antiquity the lynx was supposed to be endowed with an extraordinarily powerful eyesight, but when the present President of the Accademia dei Lincei, Lamberto Maffei, assessed the visual acuity of two lynxes experimentally with the evoked-potential method, it turned out that the lynx eye can resolve at most spatial frequencies around 7-8 cycles per degree, similar to the cat eye, but much lower than the average human visual acuity of about 45 cycles per degree (Maffei et al. 1990). This means that if lynxes could read, comfortable reading would require characters 6-8 times larger than those normally read by humans.

2. Visual sensitivity and visual acuity.

The fact is that there are several aspects to visual function: the eyes of cats and lynxes are very good at detecting the presence or absence of light in their environment, but not as good in telling apart two adjacent objects or in perceiving the fine details of a visual scene. These two distinct visual properties, i.e. two-point resolution as a measure of visual acuity, and sensitivity to light were already known and tested in antiquity based on the observation of celestial bodies. An early test of visual acuity, the Arab eye test, was used as a criterion of excellent eyesight with elite warriors in the Persian army as well as with desert Bedouin hunters. It involved the ability to see Mizar and Alcor as two separate stars in the Ursa Major or Big Dipper constellation. Recent experimental work has shown that this ability correlates with "normal vision" (20/20) in the current Snellen visual acuity test, but that it falls short of maximal visual acuity (20/16 or 20/12) as presently measured (Bohigian 2008). The fact that today the ancient star test is no longer a test of excellent vision is perhaps attributable to a brightening of Alcor over the last few centuries.

With regard to the other visual function, sensitivity to light varies across the retina in an orderly way: the central area of the retina, the fovea, which in daylight enjoys maximal acuity and is used for detailed vision as in reading, becomes blind in weak (scotopic) illumi-

nation. The physiological night blindness of the fovea was probably already known to the Phoenician sailors who first navigated by the stars, but its first appearance in the scientific literature is usually attributed to the French astronomer François Arago. On page 189 of his Astronomie Populaire (1854), Arago wrote the following:
La sensibilité de l'oeil est très-variable suivant les points de la rétine où l'image vient se former. Ainsi, lors-qu'on regarde directement un très-faible étoile avec un telescope, on peut ne pas la voir, tandis qu'on aperçoit distinctement des étoiles qui ne sont pas plus brillantes situées à droite ou à gauche de la première ....en ce sens, on peut dire sans paradoxe, que pour aperçevoir un objet très-peu lumineux, il faut ne pas le regarder. (The sensitivity of the eye varies greatly according to the position of the image on the retina. Thus, when one looks directly at a very faint star in the telescope, the star becomes invisible, while similarly faint stars to the right or left of it are distinctly perceived....in this sense, it can be said, without being paradoxical, that in order to see a scarcely luminous object, one should not fixate it).

Although Arago correctly acknowledged the priority of other astronomers, such as Herschel and Cassini IV, in the description of the relative insensitivity to light of the fovea in scotopic conditions, the phenomenon is often described in ophthalmological and physiological publications under the names "Arago's scotoma" or "Arago's spot". This is not to be confused with Mariotte's structurally blind spot in the retina, which corresponds to the head of the optic nerve where there are no photoreceptors (Walls 1954). Arago also tried to offer a functional interpretation of the phenomenon named after him:
Peut-ètre expliquera-t-on le fait d'une manière très-simple, en faisant observer que le centre de la rétine étant le point qui, dans l'act de la vision est le plus frèquemment employé, doit conséquemment le premier perdre de sa sensibilité. (Perhaps the fact can be explained very simply by considering that the center of the retina is the point which is employed most frequently in the act of seeing, and therefore it must be the first to lose its sensitivity).

This tentative, wear-and-tear interpretation of the Arago's phenomenon by Arago himself was proven wrong when a proper anatomo-physiological explanation was furnished by the duplicity theory of vision, whereby the two types of retinal photoreceptors have different functions (Hubel 1988) and a different spatial distribution in the retina (Curcio et al. 1990). The cones, which are mostly in the fovea, require for their stimulation much greater luminous energy compared to the rods. They subserve high visual acuity and color vision in photopic conditions, i.e. in daylight. The rods, which are all over the retina except the fovea, are so sensitive to very dim light that a single photon can yield a significant response from a single rod. At night, in conditions of low illumination, when the fovea is blind and one sees with the rods in peripheral retina, vision is very sensitive to light but also colourless and endowed with poor acuity. The differential sensitivity of different retinal spots to light can be tested with reaction time measures using photopic stimuli, suitable for stimulating the cones, or scotopic stimuli, suitable for stimulating the rods and unable to stimulate the cones. Photopic stimuli yield shortest reaction times at the fovea, where cone density is highest, and longer reaction times in the retinal periphery, in inverse proportion to local cone density. Scotopic stimuli evoke shorter reaction times about 11 degrees lateral to the fovea, where rod density is highest, but no response at the fovea, where there are no rods (Rains 1963).

3. Reaction times and astronomers: the personal equation.

The reaction time method occupies an important position in the intertwined histories of astronomy, physiology and psychology. At the end of the 18th century astronomers were timing stellar transits using the "eye and ear" method developed at Greenwich Observatory by the Astronomer Royal James Bradley. The method involved estimating the time of transit of a star across a wire in the telescope's eyepiece by listening to a nearby clock ticking seconds. The calibration of the Greenwich clock depended critically on such procedures, and all other observations of place and time depended on the clock calibration. It is therefore understandable that in 1796 Bradley's successor, Nevil Maskelyne, dismissed his young assistant David Kinnebrook because the latter's estimations of stellar transit differed by several hundred milliseconds from those of the Astronomer Royal himself (Boring 1950; Mollon & Perkins 1996). But irreducible individual differences in perceived transit times were then found between several pairs of astronomical observers tested at the initiative of the German astronomer Friedrich Bessel. It was Bessel who coined the term "personal equation" to describe and denote a supposedly inherent individual bias in making observations, judgements and measurements. At the Neuchatel Observatory the astronomer Adolph Hirsch worked to provide the Swiss clockwork industry with a precise determination of time. He used the Hipp chronoscope, an apparatus that could measure very short time intervals, for a truly physiological rather than astronomical purpose: the measurement of the time elapsing between the physical occurrence of a phenomenon and the reported detection of that phenomenon by an experimental observer. Since this reaction time varied among different observers, its precise assessment offered the possibility to assess the personal equation of each individual and correct for it. The demonstration by an astronomer that the duration of mental processes in humans was in principle quantifiable matched contemporary physiological discoveries about a definite duration of nervous processes in experimental animals. Helmholtz and du Bois-Reymond had indeed shown that the conduction of impulses along frog nerves takes a measurable time rather than being instantaneous as previously believed.

It was the subsequent taking over from the astronomers of the reaction time method by the physiologist Donders and by the physiologist-philosopher Wundt, along with the development of a systematic mental chronometry, that gave birth to experimental psychology as a science in its own right (Boring 1950; Schmidgen 2002).

Thus, in the early and middle 19th century astronomers were the first scientists to convince themselves that the reliability of scientific observations depended on the reliability of the observer. They became aware that studying man and human psychophysiology was essential for achieving accuracy and objectivity in astronomy and other sciences alike. According to Canales (2001):

....by debating the nature of personal differences in observations and how to eliminate them, astronomers sketched different conceptions of 'man'. While some, like Hirsch, believed personal differences were due mainly to different brains, others, like Wolf, believed they were mainly due to different levels of skill and education.

Apart from the fact that education acts on and through the brain, and different levels of skill are underpinned by different brain mechanisms, there is no doubt that in trying to do away with the observer it was astronomy that created the field of mental chronometry and handed it down to experimental and physiological psychology. It seems ironic that such a strenuous attempt at getting rid of the human factor and human error for scientific accuracy in the assessment of stellar times was largely forsaken a few year later in the saga of the astronomical exploration of the planet Mars.

4. Schiaparelli and Mars.

The existence of "canals" on Mars was first reported by the Italian astronomer Giovanni Schiaparelli in 1877. These canals are now known to be non-existent after the detailed photographic analysis of the surface of Mars carried out by the Mariner and Viking expeditions in the 1970s and thereafter. My task in this meeting on the occasion of the centennial of Schiaparelli's death is to express an educated guess as to whether visual neuroscience can explain how he could have seen them. As Sagan & Fox (1975) have written:

The canals of Mars have been something of an embarassment to planetary astronomers since attention was called to their existence *by Schiaparelli in 1877. The reality of most of the canals, much less the processes producing them, has been the subject of heated controversy; and the initial hypothesis by Lowell that they were the constructs of intelligent beings on Mars has led to their general classification somewhere in the no-man's land between science and fiction.*

Percival Lowell was the American astronomer who most of all believed in the existence of the Martian canals and their construction and utilization by an intelligent Martian population. He maintained that the canals had been constructed to distribute water from the polar regions to the equatorial deserts. It is debatable whether Schiaparelli also believed that the canals he had discovered were proof of the possible existence of intelligent life on Mars. He was known as a scholar and scientist of solid reputation who tried to stick to the facts. Yet the astronomical or pseudo-astronomical work of Lowell, along with the science fiction of writers like Flammarion and Wells, may have suggested to him that his description of the red planet had indeed provided a scientific basis to the assumption of its habitability. While his official position with regard to life on Mars has been aptly defined as neutral or ambiguous and ultimately agnostic (Sheehan 1988; Canadelli 2009), Schiaparelli advanced a bizarre socio-political interpretation of the canals only in one of his more popular writings, in which he entertained the readers by describing Mars as a paradise for plumbers and socialists. Although he made clear that in proposing such views he was flying on a hippogriff, that is on the wings of fantasy, his account of hypothetical valleys, vegetations, canal geminations and phalansteries was clearly inspired by an earthly environment. In that publication there is a drawing tentatively illustrating a Martian valley and its canals: it is strongly reminiscent of the water meadows, sluices and sluice-gates of southern Lombardy, although the irrigation system of the Ganges river is also mentioned in the text. The following is a translation of Schiaparelli's speculations:

Mars must be a paradise for the plumbers! ... It will be interesting to investigate which social order is most convenient to the predicament we have described ... (and) to find out whether the interests strongly shared by the inhabitants of a valley are likely to favour, more than it is possible on this Earth, the institution of a collective socialism, such that each valley can become a Fourierist phalanstery, and Mars a paradise for the socialists! ...(in) a planet where the well-being of each person is so strongly linked to that of everybody else, wars and international disagreements are certainly unknown, and all efforts and resources are aimed at fighting the strictures imposed by a hostile Nature, rather than at fighting each other as the crazy inhabitants of another planet are always willing to do.

Schiaparelli aimed at describing Mars by means of geometrical principles and methods, and his canals were drawn as straight lines traversing very long distances on the planet (Lane 2006). It must be kept in mind that even under excellent conditions of seeing, details from Mars' surface can only be glimpsed in flashes, similar to tachistoscopic stimulus exposures in the experimental psychology laboratory. After each of such glimpses, Schiaparelli recorded the seen image by quickly sketching it, hopefully before the memory could fade. In addition the sketches were corrected and retouched at a later time upon better seeing conditions, so that the final maps were composites of many sketches performed in the course of several nights (Canadelli 2009). Therefore potential sources of error were not limited to faulty perception, but may have also had to do with false memories or with imprecise and unfaithful sketching. Already in the 19th century Helmholtz had shown that during a tachistoscopic exposure of a visual scene, one tends to see only those parts of the scene that are in spatial register with the direction of attention (Helmholtz 1867, see Berlucchi & Rizzolatti 1987). Unattended parts of the scene are not seen or are misperceived. Modern experiments have confirmed Helmholtz's findings (Treisman 2006). For example, when a red O, a blue T, and a green E were presented tachistoscopically in an unattended part of the visual field, observers reported many illusory conjunctions such as a red E or a green T (Treisman & Schmidt 1982). By focusing attention on one part of the Mars surface during a brief moment of seeing, Schiaparelli may have misperceived, and thus erroneously sketched, illusory conjuctions on other, unattended parts of the planets.

Optic and visual illusions may have also misled Schiaparelli' seeing. He may have perceptually fused minute spots or blobs, too small to be distinctly and separately defined, into continuous lines or streaks. The modern webcam electronic imaging technology has shown a few "canals" on Mars through such fusion of surface markings close to the resolution limit of the camera (Dobbins & Sheehan 2004). Perceptually distinct punctiform elements can also be fused into lines according to the Gestalt principles of grouping and good continuation (Kanizsa 1991). Further, as suggested by Sheehan (1988), at least some of Schiaparelli's straight lines may have been "subjective" contours, akin to those occurring in the compelling illusions demonstrated by the Italian psychologist Gaetano Kanizsa, whereby contours are perceived where there are none (Kanizsa 1976). It must also be considered that one often sees what one expects to see, as shown by many examples from the history of microscopy. Just to mention two instances, the preformationists of the 17th and 18th centuries believed that animal organisms are created as such rather than through the development of a single fertilized ovum (Van Speybroeck et al. 2002). As a consequence, they believed that under the microscope they were seeing fully formed small humans and animals (homunculi and animalculi) within sperms and eggs: a wishful seeing determined by a wishful thinking. In the heated debates in the neurohistology of the early 20th century, it is now clear that Golgi's stubborn and wrong defence of his reticular theory against the neuron theory of Cajal influenced what he saw through the microscope, or at least what he reported (Raviola & Mazzarello 2010).

With regard to the possible expectancies which may have influenced Schiaparelli's inspections of Mars, he may have been sensitive to the speculations and hopes about intelligent beings living on other planets that have been recurrent in human culture and science. As late as 1994 Carl Sagan wrote :

Should not there be an immense number and diversity of inhabited worlds in the Milky Way? Scientists differ about the strength of the argument, but even at its best it is very different from actually detecting life elsewhere. That monumental discovery remains to be made.

Whether Schiaparelli believed that his Mars studies could prelude to such a monumental discovery is not unlikely but is not known for sure. What cannot be doubted is that Schiaparelli's early Mars description had started a collective delusion by the canal believers which has been aptly captured by Sagan & Fox (1975):

The vast majority of the canals appear to be self-generated by the visual observers of the canal school, and stand as monument to the imprecision of the human eye-brain-hand system under difficult observing conditions where the brain is not only the material link between the eye and the hand, but also the origin of expectancies and beliefs which may influence, either rightly or wrongly, both the eye and the hand. In the early observation of Mars, the unreliable observer, whom the personal-equation astronomers had wanted to exclude from observation of stellar transit time, had made his triumphant reappearance

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