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Historical Perspective

Galileo Galilei's vision of the senses

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Neuroscientists have become increasingly aware of the complexities and subtleties of sensory processing. This applies particularly to the complex elaborations of nerve signals that occur in the sensory circuits, sometimes at the very initial stages of sensory pathways. Sensory processing is now known to be very different from a simple neural copy of the physical signal present in the external world, and this accounts for the intricacy of neural organization that puzzled great investigators of neuroanatomy such as Santiago Ramón Y Cajal a century ago. It will surprise present-day sensory neuroscientists, applying their many modern methods, that the conceptual basis of the contemporary approach to sensory function had been recognized four centuries ago by Galileo Galilei.

Introduction

In 1609, Galileo initiated telescopic observations that were of crucial importance in heralding the modern scientific revolution. The new conception of the universe, as advocated by Copernicus, placed the sun in the central place rather than the earth. To derive support for this new conception, Galileo introduced a similar revolutionary shift in the conception of sensory processing and of vision in particular.

Visual contrast and cosmology

Visual optics was transformed in Galileo's lifetime, largely as a consequence of the endeavours of two fellow astronomers, Johannes Kepler and Christoph Scheiner. Kepler described the dioptrics of the eye and Scheiner married this to its gross anatomy [1]. Galileo sought to cast light on vision by looking, with perspicacity, at the stars. He used spatial contrast and other visual phenomena to undermine received wisdom concerning the stars and the senses. Traditional cosmology conceived of heavenly bodies as perfect spheres but Galileo observed mountains and craters on the moon and variable spots on the sun (Figures 1 and 2). He used evidence based on visual contrast and 'thought experiments' (considering observations that were then impossible to make) to support his view. This led to a controversy with Scheiner (Figure 2), who was not willing to admit the existence of spots on the surface of the sun 'blacker than those seen on the Moon' [2]. Galileo stressed that the sun spots were actually brighter that the brilliant zone of the moon. He argued that vision can be fallacious and that, in order to provide useful information about reality, visual images must be compared and matched under similar viewing conditions [3,4]; this is a fundamental tenet of modern visual science. His telescopic observations of the sun indicated that the black spots are not darker than the area surrounding the sun. Having proved, through a comparison with Venus (the brightest planet), that the full moon would become invisible if placed near the sun, he wrote:

> 'If therefore the darkness of the sun spots is not more than that of the field that surrounds the Sun itself; and if, moreover, the splendour of the Moon would remain imperceptible in the brightness of the same ambiance, then, by a necessary consequence, one concludes the sun spots to be not less clear than the most splendid parts of the Moon'. [4] p. 13

Galileo's conclusion was that sun spots are physically more luminous than the shining moon but they appear darker because they are seen against the bright surface of the sun.

In the same discussion, Galileo developed another important argument regarding the nature of the surface of the moon by comparing the moon to terrestrial objects. When a room, illuminated by the sun, is connected to another by means of an aperture (subtending an angle equivalent to that of the moon) the second room appears more intensely illuminated than if it was exposed directly to moon light. Indeed one 'might be able to read a book more easily with the secondary reflection of the wall than with the first of the Moon' [4] p. 135. Subsequently, Galileo established another thought comparison between the brightness of celestial bodies and that of the earth struck by the sun. At night it might be difficult to decide whether a light appearing near the edge of a distant mountain is a (terrestrial) fire or a star low on the horizon. The earth, being on fire and full of flames, could then be confused with a star by an observer situated in a remote part of the universe. However, the earthly fire would be less intense than that induced by sunlight because a candle flame is almost invisible when viewed against a stone directly illuminated by the sun. Therefore, the earth illuminated by the sun and seen from the tenebrous part of the moon will appear bright like any other star.

Galileo used the mutual reflection of sunlight between the earth and moon to refute a fundamental tenet of classical cosmology – that they were distinguished by differences in surface perfection. The discussion of the dim light visible in the dark zone of the moon is elaborated

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Figure 1. Watercolour images of the moon painted by Galileo to illustrate his first telescopic observations (© Biblioteca Nazionale, Florence). The visible non-homogeneities were interpreted by Galileo as evidence of mountains and craters on the moon. This conclusion was based on a series of observations, interpreted with reference to the laws of geometry, perspective and vision. This related particularly to knowledge of the variable aspects of light and shadow on irregular surfaces, which Galileo derived, in part, from his knowledge of the techniques of pictorial representation [8,9].

in Galileo's last published work*. Contrary to immediate appearances, he showed that the 'dark light' of the moon ('lunar candour') is actually much more intense than the light shone from the full moon onto earth. To realize comparable viewing conditions for the two luminosities (without transporting the observer to the moon), Galileo invoked twilight on earth as an intermediate state through which one could judge the physical intensity of two visual objects. Lunar candour can be noticed in the initial moments of sunset, whereas the illumination of earth by a full moon becomes appreciable only late after sunset. Minute details can, indeed, be seen on the surface of the earth in twilight that are invisible in the middle of the night even with a full moon. Moreover, the shadow of a terrestrial object produced by the full moon becomes appreciable only in late phases of twilight. Finally, long after sunset, distant and elevated buildings can be seen, which might be invisible in full moon light. Thus, Galileo concluded that illumination of the obscure part of the moon due to irradiation of sun light from the earth is more intense than the light reflected from the moon onto earth.

Galileo displayed a particular awareness of the global visual context (spatial contrast and background illumination) in the estimation of physical luminosity. Subjective estimations of brightness were open to error and so he made

* Galileo's text was written in 1640 in the form of a long letter addressed to Prince Leopold of Tuscany. It was published in 1642 inside the work of Fortunio Liceti *De Lunae subobscura,* Schiratti.

Figure 2. *Sun spotters* by Nicholas Wade. Portraits of Christoph Scheiner (left) and Galileo Galilei (right) are combined with the title pages of their books on sunspots [2,4] and their respective representations of them. For Scheiner, the sunspots could be accounted for by temporary aggregations of satellites that, during their revolution, partially occluded its visibility. In his retort, Galileo employed geometrical perspective and visual phenomena to show that the spots were close to the surface of the sun and developed important reflections on sensory mechanisms.

recourse to alternative indices of physical light intensity. In modern terminology, many of his (thought and real) visual experiments could be considered as 'psychophysical' (Figure 3). His approach to the senses is particularly evident in a letter (of 1611) addressed to Christoph Grienberger [5], in which he discussed the objection of the Jesuits to his own assertion that mountains are present even at the extreme border of the moon, despite the absence of visible telescopic irregularities there. After explaining how he reached the conclusion (see legend to Figure 1), he pointed out the intrinsic ambiguity of images of the moon presented to the eye (even with the aid of the telescope), and of any other visual image, particularly for a distant observer. By saying that nobody could argue that mountains are on the moon

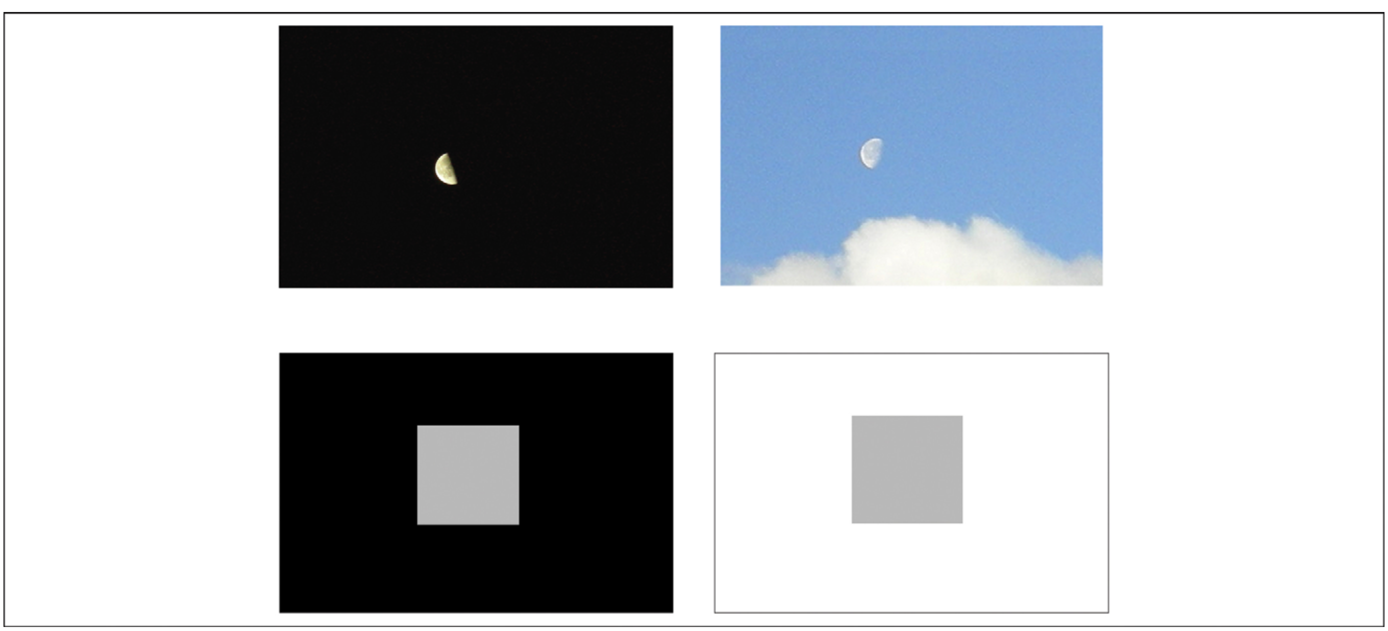

Figure 3. *Moon contrasts* by Marco Piccolino. Traditionally, the perfection of the shape and crystalline composition of heavenly bodies was invoked to account for their brilliance on the basis of a mirror-like reflection of sun light. Galileo, by contrast, argued for diffuse reflection typical of irregular surfaces; he anticipated that if the earth could be viewed against the nocturnal sky it would appear as brilliant as the moon [3,4]. He attributed the brilliance of the nocturnal moon to its visual contrast against the night sky. The diurnal moon is not brighter than other objects illuminated by the sun, such as 'certain white clouds'. In our figure, moon images are compared with a simple contrast effect of modern psychophysics whereby the same grey square appears brighter or darker as a consequence of the background. Despite its apparent brightness, the moon is physically one of the darkest planets in the solar system because it reflects rays from the sun very poorly. It is to be noticed, moreover, that the effect of visual contrast on the appearance of the moon is much more intense in real conditions than in the figure.

simply because they saw them there, Galileo was implicitly recognizing the complexity of vision that has been fully revealed in contemporary neuroscience.

Galileo's sensory philosophy

Galileo's explicit recognition of the limits of the visual process is consonant with some fundamental tenets of contemporary visual neuroscience. Vision does not simply consist of the generation and transmission of neural images faithfully resembling the optical images of the external world. It is a complex function aimed at extracting from the environment information of adaptive value; it results from the interplay between physiological and psychological processes, relying on past experience and acquired knowledge. Through these processes we could derive valuable knowledge of the external world in the absence of any definite correspondence between objective reality and sensory representations (and in spite of physical and physiological errors).

In *Il Saggiatore* (Figure 4), an important polemical work published in 1623, Galileo developed the philosophical background for his new perceptual attitude (Box 1) and explicitly negated the objective existence of independent sensory qualities such as colours and tastes, sounds and smells. To clarify the distinction between physical and psychological attributes, he referred to the sensation of tickling by developing an example already developed in a previous text [6].

> 'I move one of my hands, first over a marble statue, and then over a living man. As far as concerns the action which comes from the hand, it is one and the same for each subject, and it consists of those primary accidents, namely motion and touch; and these are the only names we have given them. But the animate body which receives these actions, feels different affections depending on which parts are touched. For example, when touched under the soles of the

Figure 4. *Galileo's Assayer* by Nicholas Wade. Galileo's portrait (derived from the painting by Francesco Villamena) is framed by the frontispiece of *Il Saggiatore* [7]. In this book, Galileo developed the philosophical background for the new approach to the senses.

Box 1. 'Sensory philosophy' from Galileo to modern neuroscience

Galileo's idea that sensory qualities are not objective attributes of external objects but that they depend upon the interaction of external agencies with sensory mechanisms entered modern neurosciences through a complex historical path. It was initially elaborated by philosophers and it entered into sensory physiology mainly through the work of Johannes Müller and Hermann Helmholtz. The only attributes that Galileo considered objective were those connected to spatiality (shape, position and size). Colour can usefully illustrate the non-existence of specific sensory qualities in the external world. Because of the characteristics of our trichromatic colour system, the same colour sensation can be produced by two lights of different spectral composition. However, an animal having a different colour system (for instance a dog or a bee) would distinguish between the two lights. This means that colour is an ambiguous attribute of light and can be specified only with reference to specific sensory mechanisms.

'I say that, as soon as I conceive of a piece of matter, or a corporeal substance,...I do not feel my mind forced to conceive it as necessarily accompanied by such states as being white or red, bitter or sweet, noisy or quiet, or having a nice or nasty smell. On the contrary, if we were not guided by our senses, thinking or imagining would probably never arrive at them by themselves. This is why I think that, as far as concerns the object in which these tastes, smells, colours, etc. appear to reside, they are nothing other than mere names, and they have their location only in the sentient body. Consequently, if the living being were removed, all these qualities would disappear and be annihilated.' [7] p. 196–197

'A wine's good taste does not belong to the objective determinations of the wine and hence of an object, even of an object considered as appearance, but belongs to the special character of the sense in the subject who is enjoying this taste. Colours are not properties of the bodies to the intuition of which they attach, but are also only modifications of the sense of sight, which is affected in a certain manner by light...Taste and colours are by no means necessary conditions under which we can know the nature of the object. They are linked with the appearance only as contingently added effects of the special character of our organs.' [10] p. 34–35'...there is no sound in the world without a living ear, but only vibrations, without a living eye there would be no light, no colour, no darkness in the world, but only the imponderable oscillations that correspond to light and its matter, or their absence.' [11] p. 261'...we should realize quite clearly that without life there would be no brightness and no colour. Before life came, especially higher forms of life, all was invisible and silent although the sun shone and the mountains toppled.' [12] p. 85

feet, on the knees, or under the armpits, in addition to the ordinary sensation of touch, there is another sensation to which we have given a special name, by calling it 'tickling'. This affection belongs wholly to us, and not a whit of it belongs to the hand. And it seems to me that it would be a serious error if one wanted to say that, in addition to the motion and the touching, the hand had in itself this distinct capacity of tickling, as if tickling were an accident which inhered in it.' [7] p. 197–198

To account for sensations (such as thermal, gustatory and olfactory) that could not be explained on pure mechanical grounds, Galileo invoked the intervention of minute bodies emanating from external objects and capable of stimulating the specific senses ('minimal corpuscles' or simply 'minima'). He was clearly inspired by the atomistic theories of ancient Greek science, which were then having a great revival, particularly after the circulation of Lucretius's *De rerum natura*. Matter emanating extremely minute particles in rapid motion (a basic tenet of classical atomism) enabled Galileo to provide a link between external objects and the senses, within the framework of his mechanistic theory. The minute corpuscles would stimulate sense organs and produce different sensations mainly according to the sense stimulated and 'to the multitude and speed of those minima'.

Galileo's conception represents a breakthrough in understanding the relation between the universe and sentient individuals and anticipates some fundamental principles of current sensory neuroscience. For most scientists and philosophers since Aristotle's time, there were specific qualities in the external world called 'sensibles', which were selectively aimed at interacting with the senses of animals (and particularly the five senses of humans) to produce sensations. Two main types were distinguished, the 'proper sensibles' and the 'common sensibles'. Proper sensibles were those connected uniquely with a specific sense, such as colours for vision, odours for olfaction and flavours for taste. Common sensibles were those that could be detected by the interplay of various senses such as shape, dimension, number, position and movement.

Aristotle also described 'sensibles by accident', that is, those sensibles commonly, but not necessarily, associated with the perception of proper sensibles. For Aristotle, senses are, in principle, veridical, and errors can occur on the basis of accessory circumstances or of erroneous judgements, but never for proper sensibles. There cannot be errors in the perception of white or black but there can be in their association with a particular object.

Galileo's general conception of sensory processes is deeply innovative and it paved the way for the development of modern sensory neuroscience. By stating that tastes, smells, colours and so on would have no existence in the absence of the individuals endowed with sensory capabilities, Galileo, in marked contrast to the dominant Aristotelian tradition, was stipulating that nature does not contain specific signals for sensory communication with living beings. Put in other terms, there is no specific language through which nature talks to living beings (and especially to humans) by signs especially adapted to their sensory processes. For Galileo, sensations followed actions exerted on the perceiving individual by purely objective elements, lacking any definite sensory attribute. These elements were equated with matter in movement of diverse rarefaction or subtlety.

Leaving aside the mechanistic aspects, this is the epistemological conception that underlies modern sensory neuroscience. In the external world there are no flavours, odours, colours or sounds, but only molecules and mechanical or electromagnetic waves (or other forms of energy). All this exists independently of sentient individuals. Throughout evolution, sensory systems have arisen and become adapted to exploit these moving molecules or energies to gather the information about the external (or internal) world. By themselves, however, molecules have neither taste nor smell, mechanical vibrations are not intrinsically sonorous and electromagnetic waves are not coloured. Sensory qualifications arise from the interaction of the objective environmental elements with specific biological systems, but all evolved in such a way as to interact effectively with them. Not only the characteristics but also the very existence of these qualifications depends on the features and existence of those biological systems. If they were removed, sensory qualities would lack any definite reality.

In his criticism of the old scientific and philosophical tradition, Galileo was aware that a conception such as Aristotle's proper sensibles would have implied an unjustified multiplication of the attributes of the external world. This would have occurred as a consequence of the variety of external things with which they would have interacted. Within the Aristotelian view, any new dimension of sensitivity would require a new proper sensible. The number and characteristics of these proper sensibles, thus, would depend on the number and characteristics of the sentient individuals – a position that Galileo considered to be unjustified. This difficulty was one of the reasons why Aristotelians tended to restrict the number of senses to five and to refute the possibility of new sensations.

Galileo's support of the new cosmology was not solely astronomical. A world characterized by definite sensory qualities specifically adapted to human senses was diametrically opposed to his basic principles regarding the reality of nature; these are in deep contrast to the finalistic conception of the world in Aristotelian and Christian philosophy. Although the universe could be known to humans, it was not specifically constructed to be comprehensible for them. Nature was regulated by laws which are 'inexorable', independent of human understanding.

Conclusion

Galileo conceived of sensory qualities as consequences of interactions that are oriented to objects rather than humans. Because this interaction was not inscribed within a providential organization of the world, it did not guarantee against the possibility of errors, which can arise in various ways and are expressions of the limitations of sensory mechanisms. However, humans can arrive at an understanding of reality if they are aware of the limits of their senses and submit the sensory appearances to the scrutiny of reason ('the eyes of minds').

The Copernican heliocentric conception removed humans from their privileged position in the universe, and Galileo's new science deprived humans of their privileged access to the special language of nature. This was a price that human arrogance had to pay to extend its inquisitive power. It also provided novel avenues for investigating sensory physiology – so new that it has taken four centuries for us to appreciate the importance of Galileo Galilei's reflections on the senses.

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