1 Introduction

I don't think we did go blind, I think we are blind, Blind but seeing, Blind people who can see, but do not see.

—Jose Saramago, *Blindness*

1.1 Blind Vision, a Paradox?

Can a blind person see? It may seem strange to ask such question at all. "Blind vision" indeed sounds like an awkward if not impossible binomium. But this is because we are used to thinking about vision strictly in terms of "seeing with the eyes." In fact, "to see" does not only require functioning eyes and optic nerves (peripheral structures), but also functioning brain structures. Peripheral (ocular) blindness only affects part of the circuit subtending vision: although blind individuals lack the visual input, their "central hardware" is spared. In this perspective, it appears less paradoxical to question whether the brain of a blind person can see, at least when we conceive of "seeing" as the ability to generate internal mental representations that may contain visual details. We don't pretend that this position is original—Plato had already used the same word, *idein,* to designate the act of looking and that of having an idea—still, we like to stress the logical possibility of "vision" in the blind, as far as this is regarded as an *imagery* process. And with this further open possibility (still to be verified): that crossmodal recruitment phenomena or brain stimulation may also induce some visual *qualia* in the blind.

A typical exercise that is proposed to explain how imagery works is to close the eyes and think about something familiar, such as a close friend, the kitchen table, a landscape we have admired. It's often impressive how vividly we can visualize these things in our mind, either when we imagine them or when we dream. "Have you ever had a dream, Neo, that you were so sure it was real?" asks Morpheus in *The Matrix*: "What if you were unable to wake up from that dream, Neo? How would you know the difference between the dream world and the real world?" Indeed mental images share many characteristics with their original visual percept. Nonetheless, we can also

easily create a mental image of something that we have never seen: for instance, when a friend describes her/his new sofa and we can clearly "visualize" it in our mind. Without a doubt, our imagery processes are mainly visually shaped, and this because we normally rely on visual input in perceiving the world.

This, nevertheless, does not imply that a blind person cannot experience vivid mental representations of a friend's new sofa or of his/her own kitchen table. Touch and hearing can provide sufficient information for a blind person to generate a reliable internal representation of the external world. In fact, we can extract the shape of an object by touching it as well as by seeing it, we can identify and localize a person that is speaking through hearing his/her voice as well as through vision, and olfactory information also offers important details about objects (and people) and about where they are in space. Indeed, there are regions of the brain that, even when there is no sensorial deficit, process information regardless of its original sensorial source and respond to a specific object when this is either seen or touched (Pietrini, Furey et al. 2004). In this regard, mental representations do not "strictly" need vision, but may be generated through information acquired in other sensory modalities or by accessing semantic information stored in long-term memory. Notably, visual characteristics are also part of the semantic knowledge of a blind person: in other words, the congenitally blind know perfectly well that a banana is usually yellow, although they have never experienced this "yellow," and although the "pregnancy" of colors as a semantic category may be different in the blind compared to the sighted (see Connolly, Gleitman, and Thompson-Schill 2007). Hence, there are no *a priori* reasons to argue that a blind person cannot generate internal mental representations of the surrounding environment using tactile, proprioceptive, auditory and olfactory information, and relying on conceptual semantic knowledge.

Of course, one may object that blind individuals' mental representations are not comparable to those of the sighted so that, for instance, while sighted persons can picture in their mind a square in the form of a simultaneous image, a blind person can only represent it in the form of a "motor" trace, reflecting the successive movements associated with the tactile exploration of a square object. We disagree with this view. In fact, as we will argument throughout this book, we think that shapes and space are represented in an analog format in the blind (e.g., a line appears as a line, and not as a tactile memory trace), though with some intrinsic differences that derive from their dominant sensorial experience.

This book is about the effects that blindness and, more generally, different types of visual deficit exert on the development and functioning of the human cognitive system. There are a number of critical questions that can be addressed through the investigation of the nature of mental representations in congenitally and late visually impaired individuals. First of all, data can shed light on the relationship between visual perception, imagery, and working memory, clarifying the extent to which mental

imagery (and more generally, the development of the cognitive system) depends upon normally functioning vision. Studying intersensory mechanisms in the blind may also help disentangle the functional and neural relationships between vision and the other senses, and may clarify whether and how "supramodal" mechanisms are affected by the absence of one sensory modality: Is vision necessary for the development of supra-modal representations of objects (and space) and for normal intersensory interactions? Furthermore, studying both the totally blind and severely (but not totally) visually impaired individuals helps to shed light on which specific aspects of visual experience (e.g., binocularity, visual acuity, visual field) are critical for a correct cognitive development and/or for specific cognitive mechanisms. As we will discuss in the book, many variables—apart from the type, severity and etiology of visual deficit—may influence cognitive development and performance, such as the onset-time of the sensorial deprivation (congenital, early or late), the duration of the visual deficit, and other factors such as personal expertise and motivation. Finally, studying the blind offers the opportunity of knowing more about an extraordinary capacity of the brain: *plasticity*. In fact, the way the brain develops is mediated by everyday experience, and although this holds true especially in the first years of life, in adulthood brain structures still remain susceptible to experience-dependent changes: accordingly, portions of the brain that are not used due to the absence of the relevant percept—such as the visual cortex in blind or the auditory cortex in deaf individuals—may be reorganized to support other perceptual or cognitive functions. Moreover, in the absence of vision, the other senses work as functional substitutes and thus are often improved (i.e., sensory compensation), allowing blind individuals to interface with the external world and to cope with their everyday activities.

Our brain, indeed, doesn't need our eyes to "see": how this happens in blind and sighted individuals is the topic of this book.

1.2 The Tyranny of the Visual

Our culture is undoubtedly shaped by the visual: TV, computer interfaces, print images, written text, visual arts, photography, architecture, design—all of these are basic means we rely upon to acquire relevant information about what happens around us (Arlen 2000). Of course, most of our cultural experience of media is a hybrid of text, images and sounds, but still the visual format certainly plays the greatest role. This has not always been the case though: in a famous essay on this topic, "The Gutenberg Galaxy: The Making of Typographic Man," Marshall McLuhan (1962) analyzed the effects of mass media, especially the printing press, on European culture and human consciousness and argued that the invention of movable type was the decisive moment in the change from a culture in which all the senses played an important role in conveying cultural meanings, to a "tyranny" of the visual. Nowadays, although

the Gutenberg era has come to an end and given way to the *electronic era* (in McLuhan's words), the tyranny of the visual is still obvious. However, a certain visual "prepotency" is not just culturally derived but likely has deeper biological bases, as suggested by the fact that it has also been observed in other species such as rats, cows and pigeons (Shapiro, Jacobs, and LoLordo 1980; Kraemer and Roberts 1985; Uetake and Kudo 1994). In fact, the majority of biologically important information is received visually.

But why is vision so important in our life? The answer is quite pragmatic: because the visual is "easy." In other words, when processing the stimuli coming from differ- ent sensory channels, individuals rely on the modality that is the most precise or accurate for a given task they are engaged in or preparing for (Welch and Warren 1980; Ernst and Bulthoff 2004). Now, imagine the situation of having to cross the street: normally you look left and right to see whether a car is coming. Actually, you could also look straight ahead and just pay attention to the sound of cars coming from one side or the other, but you never trust your hearing so much; what you always do is to turn your head and—only after having *seen* no car approaching—cross the street. Indeed, with a single gaze we can simultaneously embrace an enormous amount of information, and our foveal acuity allows us to focus on very detailed characteristics of what we are perceiving. Moreover, vision allows us to calibrate and coordinate movements in space, such as locomotion and hand gestures (just try to walk straight ahead or put a fork in your mouth while keeping your eyes closed. . .). Hence, thanks to the fact that of all the senses it has the greatest spatial resolution, vision is usually the primary sensory modality in spatial cognition and object identification (Rock and Victor 1964; Pick, Warren, and Hay 1969; Posner, Nissen, and Klein 1976; Power 1981; Heller 1992; Thinus-Blanc and Gaunet 1997; Eimer 2004), and is likely to offer a sort of "default" reference frame for multisensory and sensorimotor integration (Putzar, Goerendt et al. 2007). Interestingly, visual dominance may also derive from an original "weakness" of the visual system: in particular, Posner et al. (Posner, Nissen, and Klein 1976) hypothesized that humans have a strong tendency to actively (i.e., endoge- nously) attend to visual events in order to compensate for the poor alerting properties of the visual system (in comparison with the auditory or tactile systems; see also Spence, Nicholls, and Driver 2001; Spence, Shore, and Klein 2001). Accordingly, both animals and humans have been found to "switch" their attention more toward the auditory modality under conditions of high arousal in order to react more rapidly to potential threats (Foree and LoLordo 1973; Shapiro, Jacobs, and LoLordo 1980).

One of the most paradigmatic examples of visual dominance, or *prepotency*, has been described by Colavita (1974) (for early reviews, see Posner, Nissen, and Ogden 1978; and Welch, DuttonHurt, and Warren 1986). In Colavita's study, participants were asked to press one button whenever they heard a tone, and another button whenever they saw a light. In the majority of trials, only one stimulus (a tone or a

light) was presented unpredictably, and participants responded both rapidly and accurately. However, a few trials interspersed throughout the experiment were bimodal, consisting of the simultaneous presentation of a tone and a light. Strikingly, in these bimodal trials, participants almost never responded to the sound and a number of subjects reported not to have even heard the auditory stimulus in that condition. Interestingly, participants typically responded more rapidly to the auditory targets than to the visual ones when these were presented in separate blocks of experimental trials. Another typical example of visual dominance is the "ventriloquist effect" for which the ventriloquist voice is mislocated toward the doll (see Bertelson 1999). Similarly, kinesthetic perception may also be misplaced toward simultaneously presented visual cues that appear elsewhere (Pavani, Spence, and Driver 2000).

The evidence discussed above suggests that the absence of vision must profoundly impact the perceptual experience of a blind person, affecting the ways in which their other senses interact and shaping their cognitive development. The next chapters will discuss whether this is the case.

1.3 Overview of the Book's Contents

There were several possible ways in which to organize the contents of this book, and we changed the chapter order several times before deciding to present it as it now stands. In fact, after weighing the costs and benefits of various orders, we decided that the best way to start a book like this was to begin with the "origin." And the origin, in our view, is our senses.

If vision is lost in the blind, then audition, touch and olfaction are still functioning and they represent the channels through which a blind person gets to know about the world. It is commonly believed that—on average—blind individuals possess a special talent for music, that they can discern voices more accurately than sighted people, and that their sense of touch and their olfactory capacities are improved (as in *Scent of a Woman*, where Al Pacino plays a late blind man who is surprisingly knowledgeable about women's perfumes). Beyond such common folk-beliefs, there is indeed experimental evidence that—where vision is lost or has never been present— other senses, and in particular touch and hearing, may gain acuity. Chapter 2 will offer a review of studies that have investigated sensory compensation phenomena in blind individuals, also discussing the implication that sensory changes play at a higher cognitive level. Moreover, the effect of blindness on intersensory interactions is considered: in fact, it has been hypothesized that visual inputs act as the driving force for setting up a common external reference frame for multisensory integration and action control (Putzar, Goerendt et al. 2007; Röder, Kusmierek et al. 2007). In this perspective, the lack of vision affects not only the way each of the other senses develops, but also the way in which multisensory information is treated.

Chapter 3 represents an "exception" in the structure of the book in that it doesn't directly deal with blindness. Rather, this chapter offers an overview of what has to be meant when speaking of "mental imagery" and "working memory," and provides a theoretical framework (and a basic lexicon) for understanding how imagery processes are possible in the blind and why they are so important for cognition. It will be clarified that mental images—whether essential or epiphenomenal (see the "imagery debate")—are of critical importance in domains such as memory, reasoning and creative problem solving. Moreover, behavioral and neuroimaging findings will be discussed, showing that although imagery can be viewed as a "quasi-pictorial" form or representation, analogous to perceptual experience, mental images are the result of complex processes which are similar (but not identical) to perception and in which long-term memory also plays a critical role.

Chapter 4 explores the functional characteristics and properties of mental images in blind individuals. It will be stressed how congenital/early blindness does not prevent the capacity to generate mental representations in an "analog" format, although these conditions are associated to specific limitations, mainly due to the characteristics of blind individuals' dominant perceptual experience. In fact, haptic and auditory experiences are necessarily *sequential*: the actual surface that can be simultaneously touched by our hands is limited (and fine discrimination only pertains to the fingers' tips), and even if we can perceive many auditory inputs at the same time, in this situation our auditory discrimination is poor and we often need to rely on short-term memory to "reconstruct" what we have heard. Conversely, vision generally allows parallel processing of multiple distinct inputs as well as their integration into a unique, meaningful representation, maintaining a high discrimination power. This different way of acquiring information plays a critical role in determining the performance of blind and sighted individuals in tasks which tap in on mental representation capacities. The analysis of similarities and differences between sighted and blind individuals' performance also extends our understanding of functional "supra-modal" mechanisms within the human brain, which are capable of processing information regardless of its sensorial format.

Many researchers agree that spatial features play a major role in the generation of mental representations, providing a general "schema" that can then be fitted with other sensorial details. In fact, spatial mental representations are extremely important in everyday life, allowing individuals to orient in their environment, localize objects in order to interact with them, and so on. Not surprisingly, due to its greater spatial resolution, vision is usually the dominant sensory modality in spatial cognition. Chapter 5 describes how blind individuals represent peripersonal/near and extrapersonal/far space. Findings will be reported showing how the blind tend to rely on an egocentric/body-centered reference frame when representing objects in space and to generate "route-like"/sequential mental representations in navigation, whereas sighted

individuals are able to generate allocentric mental representations (in which objects' locations are represented regardless of the observer's position) and to create "survey-like" representations of the navigational space. The importance of proper mobility and orientation training and of external devices (e.g., the voice system, auditory spatial displays) to support spatial cognition in the visually impaired will also be considered.

Research with completely blind subjects offers an "all-or-nothing" perspective on the impact of visual deprivation on cognitive abilities. Conversely, investigating whether and how different degrees of visual impairment differentially interact with cognitive processes sheds light on the *specific* aspects of the visual experience (i.e., visual acuity, visual field) that are critical in shaping cognitive mechanisms. Chapter 6 considers the case of "low-vision" individuals who suffer from a severe but not total visual deficit due to different pathologies (amblyopia, glaucoma, macular degeneration, retinitis pygmentosa, etc.). Findings will be reported showing how even a partial loss of sight can induce compensatory sensory phenomena and cortical plasticity changes and can affect cognitive processes. The particular case of individuals affected by monocular blindness will also be considered so as to explore the specific role of binocularity in modulating higher-level processes.

Research into the effect of blindness on cognitive abilities is usually carried out with individuals suffering from a congenital (or early) pathology. This reduces the effect of individual differences and allows researchers to evaluate the effects of functional and cortical plasticity in a homogeneous sample. However, the case of late blindness deserves specific attention because—by forcing a change in pre-existing normal strategies—it sheds light on whether and how the brain can reorganize its networks to deal with the new sensory experience. Overall, in chapter 7 we will see how having benefited from years of normal prior visual experience can result in certain advantages for the late blind over congenitally blind individuals in different cognitive tasks; at the same time, however, compensatory mechanisms are likely to be less robust in the case of a late onset than in congenital/early blindness. In fact, in evaluating the perceptual and cognitive skills of late blind individuals, the role of onset-age and duration of the visual deficit need to be considered. The case of late blindness deserves our attention especially in light of an increasing aging population in the developed world, for which rehabilitation and ad hoc training programs should be made available.

Finally, chapter 8 offers a summary of the most relevant findings on intramodal and crossmodal cortical plasticity phenomena occurring in case of blindness. Data from neuroimaging studies (based on functional magnetic resonance: fMRI, and positron emission tomography: PET), event-related potentials (ERPs) and transcranial magnetic stimulation (TMS) will be discussed. Notably, besides intramodal and crossmodal reorganization, the brain of blind individuals maintains a similar organization

to that of sighted subjects in many respects, as is shown by the organization of the ventral ("what") and the dorsal ("where") streams. This supports the view that many areas of the human brain are "supramodal," i.e., they can elaborate information regardless its original sensory format.
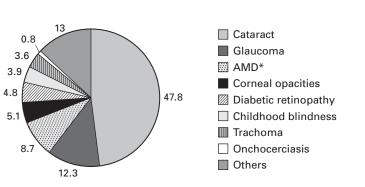
1.4   Out of the Gutenberg Galaxy: Estimates and Definition of Visual Impairment

As we have summarized above, this book is more about the implications that blindness and visual impairment have at the cognitive and cortical levels than about optometric and ophthalmologic aspects of these conditions. Nevertheless, in order to better interpret the studies that we will review, it is important to get an idea of what we refer to when using the terms "blindness" and "visual impairment."

Indeed, "blindness" and "visual impairment" are very broad categories and different scales are used across countries to classify the extent of a visual deficit, making it difficult to precisely estimate the number of visually impaired individuals. In 2002, the World Health Organization (WHO) estimated that the number of visually impaired people worldwide was around 161 million, including 37 million individuals affected by blindness (Resnikoff, Pascolini et al. 2004). More recent estimations suggest that some 259 million people worldwide are affected by visual impairment: 42 million individuals with blindness and 217 million with less severe visual impairments (Dandona and Dandona 2006). However, when also considering individuals who are affected by low vision from uncorrected refractive errors, the number is even larger: in the vicinity of 314 million (Resnikoff, Pascolini et al. 2008).

Classification criteria for blindness and other forms of visual impairment are mainly based on measures of visual acuity and visual field. Visual acuity measures the sharpness of an individual's sight and is expressed as a fraction: the numerator indicates the maximum distance (in meters or feet) at which a person can stand and discriminate between two given objects, whereas the denominator refers to the usual distance at which a person with no visual deficits could discriminate between the same objects. Visual field refers to the total area in which a standardized test target can be detected in the peripheral vision while the eye is focused on a central point. Humans' normal visual field extends to approximately 60 degrees nasally (toward the nose, or inward) in each eye, to 100 degrees temporally (away from the nose, or outward), and approximately 60 degrees above and 75 below the horizontal meridian. The range of visual abilities is not uniform across our field of view: for example, binocular vision only covers 140 degrees of the field of vision in humans; the remaining peripheral 40 degrees have no binocular vision (due to no overlapping in the images from either eye for those parts of the field of view). Moreover, there is a concentration of color-sensitive cone cells in the fovea, the central region of the retina, in contrast to a concentration of motion-sensitive rod cells in the periphery.

According to the tenth revision of the International Classification of Diseases (ICD), blindness is defined as a best-corrected visual acuity less than 3/60 (meters), or corresponding visual field loss to less than 10 degrees in the better eye with the best possible correction, whereas low-vision (visual impairment less severe than blindness) is defined as best-corrected visual acuity less than 6/18 but equal or better than 3/60, or corresponding visual field loss to less than 20 degrees in the better eye with the best possible correction (World Health Organization 2007, http://www.who.int/classifications/icd/en/). If low vision is often characterized by low visual acuity and by a reduced visual field, other common types of visual deficit may affect contrast sensitivity and color vision, or result from an imbalance between the two eyes. *Contrast sensitivity* refers to an individual's ability to see low-contrast targets over an extended range of target sizes and orientations. In other words, contrast sensitivity is the visual ability to see objects that may not be outlined clearly or that do not stand out from their background; the higher the contrast sensitivity, the lower the contrast level at which an object can be seen. Many individuals—for instance cataract patients or individuals affected by diabetic retinopathy—may have good visual acuity, but still notice a loss of their visual capability. In all these cases, contrast sensitivity testing can provide a "real world" measurement of a patient's functional vision. *Color blindness* refers to the inability to perceive differences between some of the colors that normally sighted individuals can distinguish. Color blindness can be either acquired—due to eye, nerve or brain damage or exposure to certain chemicals—or more commonly, is congenital; it can be total or partial, and can take different forms (e.g., monochromacy, dichromacy, anomalous trichromacy). Another particular form of visual impairment consists of an imbalance between the two eyes that—in extreme cases—can result in partial or complete blindness in one eye. The most common cause of monocular blindness is *amblyopia* (from the Greek, *amblyos* = blunt; *opia* = vision), which affects 2–4 percent of the population (Ciuffreda 1991), and might derive from several conditions that degrade or unbalance vision prior to adolescence, including strabismus, image degradation (due to different causes, such as astigmatism and anisometropia) or form deprivation (for instance, congenital cataract and ptosis, i.e., drooping of one eyelid) (Doshi and Rodriguez 2007). In amblyopia, the brain favors one eye over the other: the less-favored eye is not adequately stimulated and the visual brain cells do not mature normally. In fact, although ocular examination and initial retinal function appear normal in amblyopia, processing abnormalities have been reported in the retina and primary visual cortex (for recent reviews, see Li, Klein, and Levi 2008). The severity of amblyopia depends on the degree of imbalance between the two eyes (e.g., dense unilateral cataract results in severe loss), and the age at which the amblyogenic factor occurs (cf. McKee, Levi, and Movshon 2003; Li, Klein, and Levi 2008). Nowadays, amblyopia is often successfully treated by patching the unaffected eye in infants and children, but has long been widely considered to be untreatable in adults (e.g., Mintz-Hittner and Fernandez 2000).

Global Causes of Blindness in 2002

Figure 1.1 pie chart with segments labeled: 13, 0.8, 3.6, 3.9, 4.8, 5.1, 8.7, 12.3, 47.8. Legend: Cataract, Glaucoma, AMD*, Corneal opacities, Diabetic retinopathy, Childhood blindness, Trachoma, Onchocerciasis, Others.

*AMD = age-related macular degeneration.

Figure 1.1

Global causes of blindness as a percentage of total blindness in 2002. Reprinted with permission from Resnikoff, Pascolini et al., "Global data on visual impairment in the year 2002," *Bulletin of the World Health Organization* 82 (11) (2004): 844–851.

The incidence of visual impairment in the population is not homogeneous throughout the world, following both socioeconomic factors and individual differences. Approximately 87 percent of visually impaired people live in developing countries, and females have a significantly higher risk of being visually impaired than males, in every region of the world and regardless of age. Overall, the most frequent causes of blindness are cataract (a clouding of the lens of the eye that impedes the passage of light), uncorrected refractive errors (near-sightedness, far-sightedness or astigmatism), glaucoma (a group of diseases that result in damage of the optic nerve), and age-related macular degeneration (which involves the loss of a person's central field of vision) (see figure 1.1). Other major causes include corneal opacities (eye diseases that scar the cornea), diabetic retinopathy (associated with diabetes), blinding trachoma, and eye conditions in children such as cataract, retinopathy of prematurity (an eye disorder of premature infants), and vitamin A deficiency.