Representation of Space in Blind Persons: Vision as a Spatial Sense?

Catherine Thinus-Blanc and Florence Gaunet
National Center for Scientific Research

Some researchers of studies of the incidence of early visual experience on spatial abilities have demonstrated profound spatial deficits in early blind participants, whereas others have not found evidence of deleterious effects of early visual deprivation. The aims of this article are to (a) consider the theoretical background of these studies, (b) take stock of the divergent data, and (c) propose new means of investigation. The authors examine the reasons why vision plays a critical role in spatial cognition. They review the literature data. They also review the factors that could account for the discrepant data and the effects of lack of early visual experience on brain functioning. They propose that the study of strategies is a valuable option to obtain insight into early blind persons’ spatial impairment.

The ability to move about independently in space, to localize places that cannot be directly perceived because they are hidden or remote, and to plan trajectories on the basis of this knowledge is of great importance in everyday human life activities. It is not necessary to refer to sophisticated experimental studies to assert that many of these spatial behaviors depend on to a great extent visual perception. In cases where an object or a place to reach is visible, the movement or trajectory is directly guided by the visual perception of the goal or of conspicuous landmarks associated with it. In many circumstances, however, spatial behavior takes place in larger environments where the goal is not visible. In that case, it is necessary that spatial knowledge takes the form of a representation. The latter may simply consist of remembering a specific route to follow, but this simple means to achieve accurate trajectories lacks adaptive properties (O’Keefe & Nadel, 1978). The most adequate form of spatial representation is that of the topography of the environment beyond perceptual reach. This representation is acquired either by one using symbolic supports (such as reading a map) or progressively constructing one’s internal map on the basis of experience (as when one frequently goes shopping in the district in which one resides, e.g.).

If it is intuitively acceptable that vision controls many current behaviors, it is less straightforward to unravel the ways in which vision also effects the construction of internal spatial representations. For an unaware reader, this issue might appear irrelevant. Indeed, other sensory modalities, such as audition, olfaction, touch, and kinaesthetic feedback while one is walking, are also involved in spatial knowledge. Were all these modalities to have the same status as vision, spatial representations constructed on the basis of any sensory channel should have the same accuracy and properties. This appears the case when sighted participants are blindfolded and asked to perform spatial tasks with nonvisual-relevant information, which they accomplish without difficulty. Similarly, blind participants who have lost their vision after becoming an adult (late blind) are usually able to reach high performance levels. In contrast, however, many studies have provided evidence that people who have never had any visual experience (congenitally blind) or who have lost their vision in early infancy (early blind) are seriously impaired when performing similar spatial tasks. These data lead to a straightforward conclusion: Vision plays a crucial role in setting up spatial-processing mechanisms during a critical or sensitive period of development; but after these mechanisms have become functional, they appear to process visual and nonvisual spatial information equally efficiently. In view of its crucial role, vision could thus be a genuinely spatial modality.

The story, however, is more complex than this because there are many studies in the literature in which age of onset of blindness is found to have no effect on spatial performance. These data are all the more puzzling because they have been gathered typically in testing situations that are rather similar to those used by other researchers who had demonstrated impaired performance in early or congenitally blind participants.

The questions raised by these discrepant results are of importance in the domains of basic theoretical research and of practical orientation and mobility (O & M) education. First, the question is, Is there a transient period of maximum brain plasticity, a critical period after which no recovery of the deficits induced by sensory deprivation can occur? Such a time-locked period of optimum plasticity has been demonstrated in some animal species during which visual experience is especially crucial (e.g., guinea pigs, Withington-Wray, Binns, & Keating, 1990; rats, Benevento, Bakkm, Port, & Cohen, 1992; and see Greenough & Chang, 1988; Juraska, 1990; and Tees, 1986, for reviews; cats, Wiesel & Hubel, 1965, and Imbert & Buissrret,
What Is It About Vision That Could Make Its Role Critical?

In this section, we examine the reasons why early visual experience may have a crucial role in setting up system(s) for processing spatial information. We examine the advantages of vision over other sensory modalities in relation to spatial processing. On this basis, we attempt to evaluate the consequences of early blindness on the extraction of spatial invariants, which are the building blocks of overall representations, and on the form in which these representations are constructed and stored.

Advantages of Visual Information

Several researchers (Foulke, 1982; Millar, 1981a) have claimed that vision allows a "simultaneous" perception of the environment. However, this assertion needs qualification because only a restricted part of space can be foveated (locally attended to) at any one time. Similarly, peripheral vision provides information about a limited part of the environment. Eye movements between objects that are far apart are quick, and many see-saw motions can take place in a short time. Therefore, the haptic perception of a small environment by blind persons requires as much cognitive energy as that of sighted persons in a large-scale layout, parts of which are beyond their perceptual "reach." This is an old idea. As long ago as 1637, in Le Discours de la Méthode, Descartes (1973) argued that, when involved in the process of perceiving, one is like a blind man who explores objects with a stick. Information, which is fragmentary and sequentially collected because of perceptual limitations, must be reconstructed into a whole for the process of perceiving to be complete and accurate. Understanding any spatial configuration involves a reconstruction. It is usually the same in visual perception. Only one restricted zone of visual space can be foveated at any one time, implying that previously acquired information has been kept in memory to be related to the information extracted from the currently fixated region of space. The same applies to haptic perception but with longer delays between the processing of each of the items. Within small-scale situations (i.e., corresponding to the extent of the visual field), vision is the only sensory modality that allows information to be maintained about one item (in the peripheral field), while another one is being foveated and examined. Any spatial advantage gained by late blind persons results perhaps from their ability to understand a spatial arrangement as a whole, having formally experienced such simultaneity.

The amount of information available from the visual world is another factor that could explain why vision has advantages over other sensory modalities such as audition. Every object likely to participate in the process of spatial knowledge has visible features, but it does not necessarily emit sounds (or if it does, only intermittently). Moreover, by further contrast with audition, vision also allows the perception of distant, noxious, or fragile objects (Foulke, 1982). Yet, another specific feature of vision is its precision by comparison with audition, which does not provide precise information about the shape of objects (although the identification of simple shapes by sounds is possible; Hausfeld, Power, Gorta, & Harris, 1982). It is also through visual perception that distant object localization is most precise.
Estimation of the direction and distance of a sound is possible (see Middelbrooks & Green, 1991, for a review), but this appears imprecise and limited. Obviously, sound intensity varies as an inverse function of the distance from the source. However, this estimate implies that the participant has information about the sound intensity at its source to scale for distance, that is, he or she has some reference level with which to compare. Although some particular strategies are set up by blind persons to mitigate these limitations and optimize sound information (Mershon & Bowers, 1979), we must conclude that audition as a source of spatial information has severe accuracy limitations.

Another advantage that has been attributed to vision is that visual information lends itself to subtle attentional modulations. Visual attention can be both sharply focused and easily solicited; whereas haptic perception possesses the former property and audition the latter, only vision possesses both. This implies that, when no external stimulation reaches the blind person, he or she has to take action to maintain contact with the environment (von Senden, 1960), although vision has the capacity to draw a participant’s attention to external cues, which can be used as landmarks or means of reference (Millar, 1981a).

Finally, the data obtained in sensorial conflict situations are of particular interest with regard to the importance of vision by reference to other sensory modalities. For instance, Pick, Warren, and Hay (1969) found that, in sighted participants, vision strongly biased both proprioceptive and auditory localization judgments, whereas audition did not bias visual localization. Other data have been obtained by Warren and Pick (1970) in an auditory–proprioceptive conflict situation. They found that participants who were blind from birth produced pointing responses toward targets that were strongly influenced by proprioceptive information, whereas the reverse was not observed. Although this trend was also found in partially blind participants and blindfolded controls, it appeared more pronounced in congenitally blind participants. In addition, Warren (1970) demonstrated that vision is strongly implicated in auditory localization in adults. Control participants pointed at sounds more accurately in the presence of a visual environment than in its absence (eyes closed or in the dark), even though vision did not actually provide information as to the location of the sound. Pick et al. proposed the hypothesis that sighted people process and organize auditory and proprioceptive information on a visual map or frame of reference.

Warren (1974) has refined this hypothesis by making the distinction between three sensitive periods of development during which visual experience may have a critical role: The first period (between 70 and 150 days old) corresponds to the acquisition of eye–hand coordination. The visual control of hand movements represents a “basic integration of the manual and visual modes” (p. 161). The second period is centered around the development of crawling and walking. On the basis of the same principle as in the first sensitive period, vision allows the integration of locomotor activity and its perceptual results. Finally, the third sensitive period corresponds to the acquisition of language. Vision at this time would favor the use of verbal-based strategies, which may be more efficient than motor-based strategies. Indeed, although this hypothesis of a third sensitive period is highly speculative, it does remind us of the necessity to consider the verbal encoding of spatial concepts (see What Is It About Vision That Could Make Its Role Critical?).

Unlike Warren (1974), Millar (1994) did not seem to endow vision with a special status because she claimed that “no sensory modality is necessary or sufficient, by itself, for spatial coding” (p. 257). However, she emphasized the notion of “converging inputs,” which is germane to Warren’s opinion (at least concerning the first two periods of development). Absence of a sense modality would create an imbalance between inputs that normally converge. This tends to bias coding by giving a normally contributory source undue prominence. It also reduces the overlap between inputs that is needed to organize inputs in terms of reference frames. (Millar, 1994, p. 257)

Then, a common idea is that spatial knowledge requires that various channels simultaneously experience information. Data from conflict situations tend to support the hypothesis that vision plays a specific calibration role in spatial coding. However, the data do not demonstrate that vision is the only modality that can provide certain kinds of information but, rather, suggest that the modality typically provides that information.

**Consequences of Visual Information Advantages on Spatial Processing**

*Level of extraction of spatial invariants.* One prominent advantage of vision over other modalities, after the “primary” features described above, is its role in the extraction of spatial invariants. *Extraction of spatial invariants* means that the spatial properties of the surrounding world are perceived as invariant, despite the apparent motion of the array on the retina during locomotion. In this respect, vision provides the most precise information about the perceptual consequences of displacements. For example, the visual angles of objects and their angular distances vary as a function of the displacements of the perceiver. Because of the motion parallax, the rate of translation of images across the visual field is faster for nearer objects than more distant ones (Honig, 1987), and so forth. An easy and accurate distinction between transformations due to one’s movement and transformations due to object movement or a combination of object and sound movements can be made with visual modality because vision stabilizes the surrounding layout while the perceiver moves around. The explanation of early blind participants’ spatial impairment was proposed by Rieser, Hill, Talor, Bradfield, and Rosen (1992) in terms of “updating,” whereas moving is based on deficiencies in this category of mechanisms.

In blind conditions, feedback from external sources is not reliable, invariant, or necessarily correlated with movements. For example, in the case of auditory information, many of the sources of sound are themselves moving objects. Therefore, even if vision is not inherently qualitatively different from other sensory modalities, its relation with action confers on it a specific status that allows it to readily and accurately “inform” the participant about the perceptual consequences of his or her ongoing displacement.

From the foregoing, we can better understand why late blind participants’ spatial abilities are often unaffected. These participants have had the experience of visual feedback information...
generated by locomotion, and this sensitivity would remain even when visual information is eliminated. This issue has practical and theoretical implications: practical because it implies that protheses for blind people, which are often accepted with difficulty by young children (Bullinger, 1987), could only be used effectively during a sensitive period of sensori-motor development; theoretical because one may suppose that the benefit of visual experience on subsequent spatial abilities would be negligible before the onset of independent mobility or nearly immediately after, given the impact of the acquisition of locomotor skills on cognitive—spatial abilities (Acredolo, 1985, 1987; Acredolo, Adams, & Goodwyn, 1984; Pailbous & Thimus-Blanc, 1994).

The available data do not settle this question conclusively because of the long development time of humans. Most skills requiring sensori—motor coordination, such as reaching and independent locomotion (Portalier & Vital-Durand, 1989; Warren, 1974), appear during the first year of life, but spatio—cognitive skills continue their development until Ages 14 or 15 (Piaget & Inhelder, 1969).

Level of constitution of routes and maps. Whether visual cues are available during early infancy appears to affect one's latter choice of spatial strategies, which induces predominant use of particular means of spatial processing. On the basis of whether these means result in route or map (i.e., overall representation) construction, very different spatial abilities should be found after a person becomes an adult.

The distinction between routes and maps has been put forward by O'Keefe and Nadel (1978), who defined each construction's properties. Routes comprise sequences of instructions that specify changes of direction while one is traveling (e.g., "turn to my left, then turn to the right"). Routes are organized on the basis of the body referent (i.e., an egocentered frame of reference). They are characterized by serial aspects rather than spatial ones. Indeed, any one segment of the route traveled is useful only because it follows one segment and leads to another. If one of the elements of the chain is missing for some reason, then the person becomes lost. Route representations are not prone to reorganization because to do so would require inferences and other spatial judgments (see Spatial Performances of Blind Persons). They have no plasticity. Conversely, maps imply the encoding of direction and distance relationships between places, whatever the path that links them and regardless of the person's position or direction of approach. They are characterized by a high level of plasticity and rely on an allocentric (absolute) frame of reference. The construction of this frame of reference itself heavily relies on the perception of distal cues. Because complete absence of sight reduces dramatically the amount of available distal information, Millar (1994) suggested that early blind people's spatial knowledge would rely on more body-centered proprioceptive and kinaesthetic information than other less precise sources of distance (e.g., auditory) cues. That may account for early blind persons' tendency to use spatial information organized as routes rather than maps. In contrast, late blind people would continue to organize nonvisual landmarks as visual ones, that is, in a maplike form.

In fact, the distinction between routes and maps has already been proposed by Siegel and White (1975) on the basis of a large body of data from developmental studies of children. However, Siegel and White interposed several intermediate steps between routes and maps in children developing spatial representations of their environment. First, the child learns to pay attention to specific landmarks along familiar pathways. Second, on the basis of these landmarks, the child can memorize paths (or routes) in the form of a mental list of distances and directions that must be followed according to a precise sequence of motor actions (Siegel & White, 1975). At this stage, spatial inferences (detours and shortcuts) are impossible. In the third stage, a child has several distinct representations or maps that include paths traveled previously. The child can accurately deduce spatial relations between places, but such maps are restricted to familiar areas and have no relationships between them (e.g., the child has an overall representation of the district where he or she lives and of where the school is located, but there are no relationships between the district and school). Spatial problem solving can be achieved for a specific and known area; but if two places are not located on the same map, a straight-line link is impossible. Finally, the child reaches the map level when he or she links together partial representations of subspaces within the same overall representation. In the best case, mental computations strictly independent of the child's position with regard to the spatial layout can be accurately performed on such spatial representations.

The variety of levels of spatial processing proposed by Siegel and White (1975) is of interest because it points to the need for subtlety in the interpretation of the data in Spatial Performances of Blind Persons. This is not to say that early blind persons should be universally regarded as having achieved an incomplete spatial development. Indeed, Siegel and White's distinction allows us to reconsider the interpretation of early blind persons' spatial deficits. Some situations (the so-called "triangle completion" task, e.g., see Special Performances) involve the use of a very restricted part of space. The spatial information processing demanded is far less complex than the spatial organization of a district or problem-solving tests, such as inference tests that require the participant to piece together separately experienced parts of space (Rieser, Guth, & Hill, 1986; and Dodds, Howarth, & Carter, 1982, e.g.). Consequently, when discussing spatial deficits, it is essential to specify the level of processing concerned.

Level of mental imagery. In folk psychology, maps are usually confused with mental "bird's eye views" of the environment. Even if the spatial and specifically pictorial components of mental imagery are difficult to disentangle (Cornoldi, Bertucelli, Rocchi, & Sbrana, 1993), it remains that encoding information in the form of visual images is helpful to remember any kind of information. Mental—visual images condense many pieces of information into a single meaningful "snapshot," thus representing an economical means of storage.

To account for the spatial deficits of congenitally blind persons, Worcel (1951) claimed that sighted persons invariably translate tactile—kinaesthetic information into visual imagery. Similarly, on the basis of data on cross-modal "transfer" (i.e., transfer of information acquired through one sensory modality to another sensory modality) in sighted and blind participants, Pick (1974) proposed that haptic and auditory information about spatial position are visually encoded.

Early blind persons usually claim to create and use mental images, and several studies have been conducted to assess their
properties; as in the studies on spatial abilities, however, discrep-
ant data have been found (see Ernest, 1987, for a review).
Among the few experiments that deal more specifically with
mental images and spatial organization, Kerr (1983), for in-
stance, demonstrated in a mental-scanning task that congenitally
blind participants' images preserve metric spatial information
about the distances between haptically explored objects, al-
though their reaction time was longer than that needed by
sighted people.
Some visual properties observed in sighted people's mental
images—for instance, angular size diminishes with viewing dis-
tance—have not been evidenced in early blind people (Arditi,
Holtzman, & Kosslyn, 1988). That suggests that a lack of early
visual experience affects only partially spatial properties of men-
tal imagery. Sighted people's mental images include both visual
and nonvisual spatial properties (for a discussion, see Farah,
1988). Only the latter would be constituent elements of early
sensory-deprived participants' mental images.
In another type of study on mental rotation, Marmor and
Zaback (1976) showed that congenitally blind participants were
able to mentally rotate an object that was previously experienced
by touch. The participant explored the stimulus using one hand
and received the same object or its mirror image in the other
hand, with different degrees of rotation. In the three groups
(early blind, late blind, and blindfolded sighted participants),
reaction time on the matching task increased with the degree
of rotation of the second object. However, congenitally blind
participants made more matching errors and their reaction times
were greater than those of sighted people.
In a variant of the Piagetian three-mountain task, conducted
by Heller and Kennedy (1990), the participants (congenitally
blind, late blind, and blindfolded sighted) first had examined
by touch three objects in an array. Next, they were required to
identify or draw raised pictures of the object arrangement from
new vantage points. In that case, the participants did not move
but had to mentally rotate the representation of the arrangement.
No between-group differences were found in terms of drawing
performance, but congenitally blind participants' reaction times
were longer than those of sighted participants. This longer dura-
tion could be due to either a slow implementation of the same
processes as those used by the sighted participants or the use
of different mechanisms.
Another experiment by Cornoldi, Cortesi, and Preti (1991)
lends support to the idea that complex computations performed
on the basis of mental images are impaired, even in simple tasks,
for early blind participants. In this experiment, participants were
required to follow imaginary pathways, based on instructions
given verbally by the experimenter, across objects of various
complexity and made up from assembled cube-shaped building
blocks. Early blind participants showed limited abilities in com-
parison with sighted ones. However, when the pathways became
very complex (along three object dimensions), the same pattern
of errors was found in both groups. Cornoldi et al. suggested
that the early blind participants' deficit is more likely due to a
limited experience of and practice with three-dimensional ob-
jects than not constructing and using mental images. Visual
experience may create the ability to simultaneously manage a
large number of items. Early visual experience could be involved
in short-term working memory, in which case "capacity limita-
tion" (Cornoldi et al., 1991) would account for longer reaction
times. In the same vein, Heller (1989) proposed that mental
imagery can help people to remember complex sequences of
familiar objects and that the difference between sighted and
blind people in spatial tasks may be quantitative and memory
dependent rather than qualitative (Heller, 1991).

Conclusion
The advantages of vision over the other sensory modalities
appear to be quantitative in nature (more precision, greater
amount of available information, etc.). However, these advan-
tages appear to induce means of encoding spatial information
that seem qualitatively different from those which are spontane-
ously implemented by blind people. It appears easier to encode
the sequential features of a traveled route frequently repeated
in everyday life, that is, to learn the route, than to construct a
map because the extraction of spatial invariants is certainly more
difficult to perform on the basis of nonvisual information and
because there are few distant auditory and olfactory landmarks.
This spontaneous tendency to organize one's environment
through lower level processes does not mean that early blind
persons are incapable of constructing maplike representations,
but this form of encoding requires more cognitive effort in view
of the lack of visual information.

Accordingly, mental images—even if they can be constructed
by early blind persons—would be less often used for spatial
representations because learning a route requires less of this
type of mental substrate than overall representations. Therefore,
the consequence of an early lack of vision would be that (a)
the amount of information stored in the form of mental images
is diminished (or lacking) and (b) complex computations that
rely on such types of representations are more difficult.
Schematically, the unavoidable use of nonvisual information
(auditory, kinaesthetic, and haptic cues), whose characteristics are
invariably more temporal than spatial, would result in a sponta-
neous spatial organization relying more on sequences of actions
and landmarks than actual spatial relationships, regardless of
the actions executed.

Spatial Performances of Blind Persons
In this section, we review the literature relating to various
levels of spatial processing. The simplest level concerns Stimu-
lus Localization in proximal space, by reference to the partici-
 pant's position. Then, in Spatial Memory, we present experi-
ments in which researchers examined spatial relationship setups
that have been actually experienced by participants in both prox-
imal and distal spaces, either through haptic modality or walk-
ing. A higher level of spatial processing is that corresponding to
Inferential Abilities. We define the latter type of process as the
computation of spatial relationships that have not been actually
experienced but based on those already known (i.e., those be-
longing to the spatial memory type). This computation is neces-
sary for reorganizing an incomplete representation that new
spatial links are inferred. Such reorganizations have an adaptive
value because they allow the person to cope with unexpected
spatial modifications (e.g., making a detour when the usual
pathway is obstructed or unavailable, taking a shortcut, etc.).
The behaviors that result from the implementation of inferential processes represent valid tests of spatial abilities. They have been classically considered as reflecting the very property of plasticity that characterizes overall spatial representations, maps or cognitive maps (O’Keefe & Nadel, 1978; see Consequences of Visual Information Advantages on Spatial Processing).

Spatial memory and inferential processes can take place within different spheres of space. For the sake of clarity, we have made the distinction between manipulation space and locomotor space. It is obvious that processing by haptic perception of an object arrangement, for instance, shares some cognitive principles with that of a larger environment. However, there are also differences. One of them is related to the memory load necessary to acquire spatial knowledge. Haptic perception of an object arrangement takes place in a small-scale situation. Consequently, the memory load required is presumably less important than when the information is collected during a longer time course, for instance, while one is walking. In addition, in small-scale tests, the participant is often seated in front of the table on which the objects are displayed. Therefore, the encoding can be efficiently made on the basis of the participant’s static position (body referent). In only a few studies have researchers incorporated a change of perspective and updated the situation with regard to this modification.

A fourth category of situations, Use of Symbolic Representations, entails situations in which the externalization of spatial knowledge takes place within an environment of different scale and substrate than that in which the information was gathered and organized. Such conditions directly test one’s ability to transfer abstract spatial representations from one scale to another (using a map, e.g.). They differ from spatial memory and inference tests because they are aimed at examining the nature of an overall representation, without distinguishing the various specific locations where the estimation takes place.

**Stimulus Localization**

In only a few studies have researchers so far addressed the accuracy of sound localization in blind persons. In spite of this limited nature, the available data must be taken into account because any deficit observed in tasks that require higher levels of spatial processing (construction of representations) may be the consequence of an incorrect initial encoding of the stimulus location.

Wanet and Veraart (1985) have shown that early blind participants’ distance evaluation of a sound source is impaired. The deficit in distance evaluation was greater when the participants had to point with their hand toward the target than when they were required to name the coordinates of the estimated position of the sound source. In contrast, errors of direction estimation were greater when the participant gave verbal indications. In a simpler experiment, the task consisted of only the participant estimating the location of a sound with a pointer (Loomis et al., 1993; Rieser et al., 1986). As Wanet and Veraart found, in their pointing condition, Loomis et al. also did not find any group effect in the accuracy of direction estimates.

These data are in agreement with those obtained by Haber, Haber, Penningroth, Novak, and Radgowsky (1993) from a study on the effects of the nature of the response on estimation accuracy. Comparing nine methods for locating a sonorous target, they found the most accurate performance to occur when the participants had to point with a part of their body (head or finger).

In contrast, Fisher (1964), comparing auditory and tactile localization, found that congenitally and late blind participants displayed poorer performance than blindfolded sighted participants when the response consisted of turning their head toward the target but not when they were asked to verbally indicate which stimulus (of two) was farther to the left. However, in this last condition, the required evaluation was less precise than when they had to orient their head toward the target because it required only a comparison between two target sounds.

We emphasize that the observed deficits were not due to a deficient perception of auditory stimuli by blind participants. Very subtle processing of sound (probably by echolocation) is found in early blind participants. For instance, young blind participants are able to detect and avoid a small box placed along a path (Ashmead, Hill, & Talor, 1989).

In several experiments, researchers have demonstrated that auditory sensitivity is quite similar in early (Starlinger & Nienmeyer, 1981) and late blind persons (Bross & Borenstein, 1982; Kellogg, 1962) or could be even better than in sighted ones (Arias, Curet, Moyano, Joekes, & Blanch, 1993).

These discrepant data do not allow us to determine whether early visual experience plays a crucial role in the distance and direction localization of an auditory stimulus. When deficits are observed, they appear rather mild. Except in Fisher’s (1964) study, the accuracy of the responses appears related to the means by which the participant has to indicate the sound source location. When blind participants had to respond using a part of their body or a pointer, their level of performance was close to that recorded by sighted participants, but this was not the case when the response consisted of a verbal evaluation. Thus, early blind participants’ poorer performance appears related more to an incorrect evaluation of the conventional measures of length (meter) than an actual deficit in stimulus localization.

Note, however, that in all the studies above, the participant was still—which does not appear the best situation for sound localization. In some studies on auditory distance localization, researchers have emphasized the useful of dynamic cues: Listeners walking toward stationary sounds (within an intermediate range of distances) localize their distance better than stationary listeners (Ashmead, Davis, & Northington, 1995). When one is walking, the rate of change in the intensity of the sound would contribute to the evaluation of its distance. Such experiments have been conducted only with sighted participants, but it is quite possible that blind participants’ auditory localization is found to be better when they are walking than stationary.

**Spatial Memory**

In the space of manipulation. In a spatial memory task conducted by Hollins and Kelley (1988), participants stood behind a circular table and haptically explored five objects presented successively, after which they were asked to memorize the location of each object separately. The test consisted of the participants indicating with a pointer the direction of each of the five objects from the original place and then from a new pointing
place elsewhere on the table. Pointing errors were greater for congenitally blind participants from the new pointing place, but their performances rose to those of sighted participants when they were asked to actually replace the object on the table. These results were explained by an examination of the nature of the errors committed by congenitally blind participants. The represented metric features appeared globally distorted because the size of the table was minimized. This distortion explains pointing errors. In contrast, while replacing the object, the participants touched the table. That allowed the congenitally blind participants to restore the metric relations between the set of objects and the table on which the objects were displayed.

In other studies, researchers did not find any differences among early blind, late blind, and blindfolded sighted participants, using quite similar tests (see Table 1). According to some researchers, such as Barber and Lederman (1988), information was said to have been correctly encoded with respect to a stationary egocentric position, whereas Carreiras and Codina (1992) suggested that participants had relied on amodal representations to perform the task.

Note that, in all these situations, object spatial localization may be encoded on the basis of movement memory. Hermelin and O’Connor (1975) attempted to neutralize the role of kinaesthetic memory in the encoding of the parameters of a movement (length of the movement and location of its end point). After children (Ages 10–15) had experienced a standard vertical movement, they were asked to reproduce the movement exactly, indicate the end point from a different starting point, or reproduce the same distance from a different starting point. Blindfolded sighted children and early blind children performed similarly in both the reproduction and end-point location, but early blind children underestimated distance reproduction. Such data suggest that early blind persons rely on a kind of kinaesthetic memory. This is in agreement with Millar’s (1979, 1981b) hypothesis that, in reaching space, distance and direction are determined by previously memorized movements.

In general, Millar (1988) proposed that congenitally blind people would be induced to use egocentric coding strategies because the amount of distal information provided by the environment is reduced and the nature of the available landmarks is more difficult to process. Early visual experience would allow for a more accurate understanding of external spatial coordinate systems (Millar, 1981b, 1985). Thanks to that early visual experience, sighted persons are more able and likely to appreciate

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**Table 1**

**Summary of the Experiments Conducted to Test Spatial Memory and Inferential Abilities**

<table>
<thead>
<tr>
<th>Type of space</th>
<th>Study</th>
<th>Means of information collection</th>
<th>Type of response</th>
<th>No. of items processed</th>
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<td>Pointing</td>
<td>Verbal indications</td>
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<td>Spatial memory</td>
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<td>Manipulatory</td>
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<td>Carreiras &amp; Codina (1992)</td>
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**Note.** The performance level of participants who were early blind is lower (<) or similar ( = ) to that of controls. The symbols in parentheses correspond to the cases when the responses are required from a new location (change of perspective). F = free; G = guided.

* Concern distance estimations. ♯ Refers either to replacing objects or indicating with the fingers actual distances within the manipulatory space, or to actually walking between places. * Verbal indications concern the naming of successive landmarks on a route. * With a ratio scaling. ♯ Path = 250 m. ♮ 10 pairs of locations.
spatial relationships between distal spatial cues. Mild deficits have been found in the previous experiments in the space of manipulation. Therefore, egocentric encoding would be sufficient and accurate enough for a correct evaluation to be made. In such cases, the participant's body can be efficiently used as a stable reference because there is no locomotor activity. In addition, the few deficits found do not appear related to an intrinsic cognitive-processing impairment. Rather, the lack of an external anchoring, which is used by sighted participants, would not be compensated for, in some cases, by the body referent.

Another alternative explanation to early blind participants' mild deficits sometimes observed in the space of manipulation is that they would be a consequence of impaired haptic identification of patterns or objects. Indeed, although early blind participants have extracted as much information as possible from haptic perception, their performance in this domain is either similar or poorer than that of blindfolded sighted participants, in particular for unfamiliar stimuli (see Millar, 1994, for a review). In contrast, late blind participants have often been found to perform better than blindfolded sighted participants in haptic pattern identification, but this superiority has not been observed in the processing of larger size situations. Consequently, the lack of generalization of optimal processing of isolated objects or patterns to multiple object configurations suggests that processing the two types of stimulus situations does not rely on similar cognitive mechanisms. Consequently, the possibility that early blind participants' deficits (observed in a few studies, as a matter of fact) in the space of manipulation may be due to a specific impairment of processing haptic information has not received experimental support so far.

In locomotor space. Loomis et al. (1993) tested congenitally, late blind, and blindfolded sighted participants on a series of tests of varying complexity. The participants were led by an experimenter along pathways that were either straight or involved turns of various amplitudes. They were asked to reproduce the pathways without using an aid. The angular estimation of the turns was also performed by the participants using a pointer. No group differences in performance were found as a function of visual experience. In other similar experiments where participants were required to learn a route (see Table 1), no differences were found in relation to the time of onset of blindness.

Rieser et al. (1986) used a different method to evaluate the effect of early blindness on spatial memory. The participants were guided from a place (start) to six other locations, marked by objects, in an unfamiliar environment. After each visit from the start to one of the six places, the participant was returned to the start (see Figure 1). Spatial memory tests consisted of the participants pointing from the start toward the places to which they had been led. Rieser et al. found no differences between the groups in the accuracy of direction evaluations (by pointing) and in latencies of spatial memory tests.

Altogether these data demonstrate that early or congenital blindness has little or no effect on direction and distance estimation of spatial relationships among locations that have been actually visited by the participants or explored with their fingers. In this respect, Lederman, Klatzky, and Barber (1985) suggested the possibility that early blind people use "heuristics," based on exploration movements which may result in the representation of a route (Bigelow, 1991). In the same vein, Foulke (1982) suggested that blind participants constitute spatial representations in the form of a "path structure" instead of spatially related landmarks. Indeed, a rather similar type of explanation can be posed for the data obtained in the space of manipulation in terms of egocentric encoding: The knowledge of traveled pathways appears to rely on kinaesthetic memory (muscular, tendinous, and vestibular information — this last category being most important for a direction estimate on the basis of body rotations), possibly matched to the temporal parameters of the displacements (velocity of the movement, in the manipulatory or ambulatory space, and travel duration) for distance evaluation. Such a form of egocentric organization corresponds to the constitution of routes, which are usually regarded as alternatives to maps to account for spatial representations (see What Is It About Vision That Could Make Its Role Critical?).

Inferential Abilities

In the space of manipulation. Lederman et al. (1985) asked participants to freely explore with two fingers a curved path made of raised dots between two objects displayed on a table. The test consists of participants evaluating the absolute distance between the two objects with their index fingers. The interfinger distance represented their judgment. This simple task requires inferential abilities because the absolute distance between the objects had not been experienced and had to be deduced from the curved path. They found that distances were overestimated, in proportion to the length of the followed path. This overestimation was greater for congenitally blind participants and appeared to imply the use of a "movement-based" heuristic for encoding distances.

Some of the experiments above in Spatial Memory also incorporated inferential tests (Barber & Lederman, 1988; Carreiras & Codina, 1992; see Table 1). These tests consist of participants estimating the least distances between landmarks or objects that had not been linked by a pathway during the initial phase of learning. No differences between early blind and blindfolded sighted participants were found. Perceptual information avail-
able from the moving finger would have been of secondary relevance in comparison with the position encoding with respect to a stationary egocentric position (Carreiras & Codina, 1992). As self-referent coding was accurately used by congenitally blind participants, no deficit appeared in both spatial memory and inferential tasks.

In locomotor space. A simple test of inferential ability involves asking participants to localize different places in a familiar urban neighborhood. Byrne and Salter (1983) compared the ability of early blind and blindfolded sighted participants in such a task. The participants were required to make both direction (pointing) and distance (ratio scaling) judgments between their home — where the test took place — and several locations (some of which could not have been linked by the participants having walked between them) and between two of these locations by them imagining standing at one of them. Whereas the early blind participants were less accurate than the sighted participants in making direction estimates, both groups reached the same level of accuracy in making judgments. Similarly, the performance of the early blind participants was worse than that of sighted participants when the place of localization had to be imagined.

In an original study, Dodds et al. (1982) explored the spatial representations of congenitally and late blind 11-year-old children. In this case, the children were not required to walk but were taken individually by car along two mirror-image routes linking two places labeled home and goal (Figure 2). During their travel on the second route, they were asked at each bend to point to bends along the first route. They also had to draw a map of the routes. Dodd et al. rightly labeled the former task as inferential, inasmuch as (a) it implied that the children integrated two separate spatial experiences into a unified whole and (b) that euclidean spatial relationships were established on the basis of a global representation. The groups differed in their level of drawing completion and pointing accuracy. Only one of the four congenitally blind children produced a two-dimensional representation of the routes similar to that of the late blind children and made few pointing errors. According to Dodd et al., the poor-performing early blind children relied on egocentric strategies, preventing them from updating their position in the course of the journey and a fortiori from combining the two sets of spatial information to produce new responses. Similar patterns of results were found in comparable experiments conducted in smaller, unfamiliar rooms (Herman, Chatman, & Roth, 1983; Veraart & Vanet-Defalque, 1987; see Table 1 for details).

Rieser et al. (1986) examined the effects of early blindness on inferential abilities in the situation described above (see Inferential Abilities and Figure 1). Depending on the pattern of visits among the places, some links were never experienced; these were made the object of inferential tests. Unlike the spatial memory tests where no between-group difference was observed, early blind participants displayed more errors than the late blind and blindfolded sighted participants.

As we indicated in Inferential Abilities, Barber and Lederman (1988) did not demonstrate any deficit in early blind participants in a small-scale haptic version of Rieser et al.'s (1986) experiment. They rightly concluded that locomotor and manipulatory spatial processes involve different mechanisms. Indeed, when one is stationary, a self-referent encoding is sufficient. However, as soon as there is locomotor activity, the body cannot serve as a stable reference, except for the storage of a route, that is, a sequence of actions that do not require the establishment of spatial relationships between landmarks. More complex computations (inferences) involve spatial relationships among places whose links have not been previously experienced. In addition, to be efficient in performing this kind of computation, a spatial representation has to be independent of the person’s position. Then, external cues must be used to update one’s displacements with regard to the invariant environment. Keeping track of one’s position by reference to external landmarks implies a continuous updating of the varying relationships between the moving participant and the stable environment.

In sighted persons, the peripheral optic flow ("visual" kinesthesia; Gibson, 1979) while one is walking would perform this updating function. For instance, Rieser et al. (1986) accounted for early blind participants' spatial deficits during inference tests in terms of a lack of perceptual updating while he or she was walking: "Early visual experience would play a role in sensitivity to change in perspective structure when [he or she is] walking without vision" (p. 173). In late blind persons, the experience of visual kinesthesia before the loss of sight would facilitate the integration of nonvisual kinesthetic information.

Rieser et al. (1992) have confirmed to some extent Rieser et al.'s (1986) hypothesis (sensitivity to spatial change that is due to the peripheral optic flow). Participants with different types (peripheral vs. central visual field) and ages of onset of visual impairment were tested for their knowledge of a familiar rectilinear outdoor neighborhood. They had to make judgments of euclidean distances and directions among landmarks in this environment. Participants with early childhood loss of broad vision field or early blindness showed poorer spatial performance than those with an early or late acuity loss but normal peripheral field. Rieser et al. (1992) concluded that an early broad visual field "facilitates the calibration of the biomechanical cues for locomotion against distances and directions moved relative to features fixed in the surrounding environment" (p. 220). A new important element arises from this study, namely, the lack of

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**Figure 2.** The two routes (not to scale) along which the participants where driven (left) and the schematic rendition of the inferences that children were required to make from one route to the other (right). G = goal; H = home. From “The Mental Maps of the Blind: The Role of Previous Visual Experience,” by A. G. Dodds, C. L. Howarth, and D. C. Carter, 1982, Journal of Visual Impairment and Blindness, 76, p. 8. Copyright 1982 Copyright Clearance Center. Reprinted with permission.
vision in the peripheral visual field (in the presence of nondeficient focal vision) could account for spatial deficits. These data provide strong experimental support for Gibson’s (1979) theory about the spatial function of the peripheral optic flow. A series of experiments of sighted participants provides other weighty arguments to support the idea that “environmental flow,” including optic flow (in addition to other types of information, such as air flow) in covariation with biomechanical activity, calibrates distance estimations (Rieser, Pick, Ashmead, & Garling, 1995).

In addition, the explanation of the early blind participants’ deficits in terms of a lack of updating of their position by reference to the stationary layout while moving in space is complementary to the hypothesis above concerning the predominance of egocentric encoding in blind participants: The preference for a body-centered reference is related to a kind of “neglect” of the invariant features of the environment.

According to these data and hypotheses, one is tempted to conclude that, unlike a simple spatial memory tasks, situations that involve complex computations, such as reorganization, deduction, and inferences on the basis of previously stored spatial information, are deeply affected by the lack of visual experience. However, we now turn to another set of data that support the contrary argument.

Rieser et al.’s (1986) data have been directly questioned by Loomis et al. (1993). In a series of experiments (in addition to distance and turn estimations, see above), congenitally blind, late blind, and blindfolded sighted groups were asked to perform simple inference tasks, such as triangle completion. In none of these tasks was an effect related to visual experience found. Loomis et al. considered the possibility that the task may have been too simple because “the subject needed to represent only the origin and two other pivot points to perform either the retrace or completion response” (p. 84). Consequently, they replicated Rieser et al.’s experiment, which appeared to demand more memory and spatial inference than the triangle completion tasks because it involved learning the location of several objects and updating one’s position during locomotion. Loomis et al. did not replicate the finding that the congenitally blind participants were significantly worse in accuracy than the sighted and late blind participants in the inferential task. Instead, they found a trend in that direction. However, they emphasized the heterogeneous nature of the blind sample. For instance, one of the congenitally blind participants performed very poorly, whereas another one performed very well; the origin of blindness was the same for both participants. They accounted for these discrepant data in terms of the manner in which the blind participants were selected. In their case, Loomis et al. (1993) considered the possibility that the selection procedure “may have been biased toward subjects with better-than-average mobility skills” (p. 89). This issue has considerable implications with regard to the conclusions that can be drawn from the extensive set of divergent data about blind persons’ spatial abilities. We discuss this at length in Possible Factors Accounting for Discrepant Data and Toward a New Approach to Blind Persons’ Spatial Deficits.

In other studies, summarized in Table 1, requiring, for instance, triangle completion (Klatzky, Golledge, Loomis, Cicinnelli, & Pellegrino, 1995), researchers did not demonstrate spatial impairment related to the early onset of blindness.

One case study is that of a child named Kelli whose spatial abilities were analyzed in detail by Landau, Gleitman, and Spelke (1981). They reported that at 2½ years, this congenitally blind girl was able to succeed at a simple spatial inference task (Figure 3). The accuracy of Kelli’s journey was similar to that of a blindfolded sighted child of the same age. The experiment was repeated with a careful control for sound cues (a possible experimental bias, i.e., the use of echolocation), but this yielded similar results (Landau, Spelke, & Gleitman, 1984). Nevertheless, because the same child was the participant in all experiments, training may explain her good performance. It is likely that, during the course of the various tests, Kelli had had the opportunity of traveling among the locations involved in subsequent tests (for a further discussion of this experiment, see Millar, 1994).

Indeed, the different training experienced by participants may be an important element for the understanding of early blind participants’ occasional success in inferential tasks. For instance, Woroch (1951) found that, although sighted participants performed in a spatial inference task better than blind participants, there was no difference between the early and late blind participants. Rieser, Guth, and Hill (1982) attributed this result to the early blind participants’ need to base their responses on slower mental processing in this untimed task. That various means of collecting and using information may be implemented by individuals, regardless of the observed levels of performance, is of particular interest for the understanding of the discrepant data above. In summary, these data do not allow us to state definitely that lack of visual experience has no effect on high-level spatial processing, such as that involved in inference. That some early blind participants are able to perform at the same level as late blind and blindfolded sighted participants suggests that there may be hidden or neglected factors (see Possible Factors Accounting for Discrepant Data) that might reasonably account for lack of convergence among studies.

[Figure 3: A layout for a spatial inference task. B = basket; M = mother; P = pillows; T = table. 1 square = 2 x 2 ft. From “Spatial Knowledge in a Young Blind Child,” by B. Landau, E. Spelke, and H. Gleitman, 1984, Cognition, 16, p. 230. Copyright 1984 Elsevier Science. Reprinted with permission.]
Use of Symbolic Representations

The use of a map to directionally guide locomotion in space belongs to this category. Landau (1986) reported that no previous training is necessary for a 4-year-old to use a symbol map to orient himself or herself. Similarly, Leonard and Newman (1967) showed that blind adolescents were able to use threedimensional maps to follow routes that they had previously traveled, as well as to discover new routes between known landmarks and infer shortcuts in a familiar layout.

The effect of orientation of the map with regard to the participant's orientation in the environment has been investigated by Rossano and Warren (1989a). The aim of their experiment was to examine the effect of visual experience on the "alignment effect," which refers to, in sighted participants, when the map and the participant are not in the same orientation (contra-alignment or misalignment) with respect to the environment, spatial localization performance is adversely affected. Rossano and Warren, using actual maps, found greater localization errors on contra-aligned than aligned trials in both early and late blind participants. The extent of the error was similar to that found in blindfolded sighted participants (Rossano & Warren, 1989b).

That performance was not related to the onset of blindness is amply illustrated by the fact that the best two performers were early blind and the worst two were one late blind and one congenitally blind who had partially recovered sight at Age 11. These data suggest that similar rules for processing this specific type of spatial information are implemented regardless of visual experience.

Although Rossano and Warren (1989b) did not explicitly refer to the term maps, some experimental situations are very close to map use in their principles. For instance, Herman, Herman, and Chatman (1983) designed a task similar to that used by Rieser et al. (1986), but the participants haptically explored spatial relationships between an object, which served as a starting point, and three other objects. These latter objects were never related by haptic exploration. The test took place in a gymnasium. Congenitally blind participants were tested in a mirror for spatial memory and inferential abilities; in this phase, they had to walk between objects that had not been previously linked during the haptic exploration phase. Unlike Rieser et al., Herman, Herman, et al. did not find any difference between the performance in spatial memory and inference tests. However, it is unsound to compare these two experiments because the externalization of the responses was different and no control blindfolded sighted participants were tested by Herman, Herman, et al.

Another category of transfer tests consists of those requiring participants to construct a tabletop model of a familiar environment. Using this method, Casey (1978) found that congenitally blind students were not able to construct a tabletop model of their school campus as accurately as partially sighted students. Most of the congenitally blind students constructed separate piece meal sets of objects, whereas partially sighted students constructed much more organized models.

By using another situation where the participants had to learn a route in a large- or small-scale environment, Ochaïta and Huertas (1993) found no difference between congenitally and late blind adolescents in the construction of a model of the traveled route. They accounted for their data in terms of task simplicity.

Conclusion

These discrepant results make a straightforward interpretation of the early blind person's spatial deficits difficult. However, a trend emerges from the data above. Whereas spatial memory does not appear to depend on the time of onset of blindness, tasks that require inferential processes do need, in most of the cases, early visual experience to be performed successfully. The divergent data, reported in Use of Symbolic Representations, are more difficult to interpret in these terms because the situations and procedures used are very different. However, tasks that specifically rely on spatial memory (following a route, Leonard & Newman, 1967; or constructing a model of a traveled route, Ocháïta & Huertas, 1993) are performed as well by early and late blind participants. In contrast, obtaining information from a map (Leonard & Newman, 1967) or small-scale model (Herman, Herman, et al., 1983) appears to facilitate early blind participants' ability to make inferences when they are tested in the actual situation. On the basis of the data reported by Casey (1978), the reverse effect occurs when information is initially acquired in an actual environment and then used in the construction of a tabletop model of the situation. This suggests that the scale of the situation with which the participant has to become acquainted may affect the constitution of the representations.

In conclusion, although they are not numerous, several observations hint that some early blind people do eventually succeed at inferential tasks at the same level as sighted participants. These data deserve to be taken into account and further examined because of their theoretical implications. Consequently, one issue to address is whether there are some neglected factors that could account for these controversial data. Before examining possible factors, however, we briefly review the studies on the effects of early blindness at the brain level.

Effects of the Lack of Early Visual Experience on Brain Functioning

Only a few studies of the effects of early blindness on brain functioning have been conducted with humans. Such studies, which usually rely on event-related potentials (ERPs), electroencephalography (EEG), or brain imagery, are of great interest to basic researchers to better understand the consequences of a lack of early visual experience. Indeed, if differences in brain functioning are observed in groups whose performance levels are the same, this may suggest that some compensatory mechanisms or strategies were implemented to cope with the difficulty of the task. Finally, the observation of the behavior of patients who have partly recovered vision following surgery may also assist researchers to answer questions on the reversibility or otherwise of the effects of early blindness on spatial processing.

Studies of Brain Functioning

It has been found that some of the components (N2b) of the ERP of early blind participants presented with binaural tone pips and delivered through headphones was distributed more
posteriorly on the scalp than in sighted controls (Kujula, Alho, Paavilainen, Summala, & Näättänen, 1992). In addition, electrophysiological studies have shown some abnormal features of the EEG in early blind participants. The most striking finding concerns the higher negativity observed in the occipital area of these participants, by reference to blindfolded sighted ones, during two tactile tasks (Noebels, Roth, & Kopell, 1978). In another study, similar patterns of activation were found when participants performed mental rotation tasks (Rösler, Röder, Heil, & Hennighausen, 1993). During a preliminary exploratory phase, the higher occipital negativity was observed in both congenitally and late blind participants, whereas in sighted participants, the higher negativity was found in the frontal area. Note however, that in this study, no between-group performance differences were observed.

In a positron emission tomography scan investigation, the regional cerebral metabolic rate of glucose was measured in early blind participants by Wanet-Defalque et al. (1988). Glucose value was found to be highest in the striate and prestriate cortical areas. In addition, glucose value was higher in early blind than in blindfolded sighted participants, whether at rest or during the mental localization of a sound source. In another study, Uhl, Franzen, Podreka, Steiner, and Deecke (1993) and Veraart et al. (1990) found a similar localization in indices of increased cerebral blood flow.

According to Noebels et al. (1978), the visual cortex appears to have a "residual" function that is not related to any particular sensory modality, although they did not specify the nature of this function. Wanet-Defalque et al. (1988) and Uhl et al. (1993) considered the modified pattern of occipital activity to have no functional significance. They proposed that the increased activity of the early blind participants' visual cortex could be induced by a reduction of intracortical inhibition (Singer & Tretter, 1976). This reduced inhibition could be due to the survival of synaptic connections, which are known to disappear, in a kitten at least, as a result of visual experience (Innocenti, Fiore, & Caminiti, 1977). Several theoretical models have been proposed by researchers who have detailed the possible intimate mechanisms that are likely to account for the selection of synaptic connections among the large number available (e.g., Changeux & Dehaene, 1989; von der Malsburg & Singer, 1988). All have been more or less explicitly inspired by Hebb's (1949) conception of plasticity. One of the implications of these models and studies is that neuronal activity recorded in early blind participants' occipital cortex does not perform any useful function but reflects instead a lack of functional organization within this area (and perhaps elsewhere).

The activity of nonvisual areas also appears modified by a lack of early visual experience. Noebels et al. (1978) recorded extraocular EEG modifications, concluding that some of these areas, for instance, the frontal cortex, may be sensitive to the development of central visual pathways. In one investigation, early blind participants and sighted controls were examined in a positron emission tomography study while performing a control auditory localization task and another task in which they had to locate a pole using an ultrasonic echolocation device (Catalan-Ahumada, De Volder, Melin, Crucq, & Veraart, 1993). As in other investigations, abnormally high glucose use was observed in early blind participants' occipital areas when they were involved in the ultrasonic echolocation task compared with the sonorous target localization. This pattern of activity was not shown in the blindfolded sighted group. A different level of activation was found in Parietal Area 7 in each category of participants. This activity was reduced in early blind participants. These data support the idea that the effects of early visual deprivation are not limited to primary visual areas. Given the importance of the parietal area in spatial processing, this result is consistent with the observation of behavioral deficits in early blind participants' spatial tasks. On the basis of these results, Catalan-Ahumada et al. (1993) suggested that general cerebral organization takes a different form in early blind people, compared with sighted people. The large number of brain structures to which multimodal information converges and where it is processed (see Millar, 1994, pp. 48–84) supports the idea that a lack of early visual experience may have an effect on brain functioning, which goes far beyond the visual areas. In addition, the existence of numerous sites of convergence suggests also that compensatory functional mechanisms may occur when one category of sensory information is missing during development.

**Recovery From Early Blindness Following Surgery**

Studies on spatial processing when a patient's vision has been partially restored by surgery may be of interest in relation to the possible reversibility of the effects of early visual deprivation. There are only a few case reports on recovery from long-lasting early blindness. In one study, the perceptual abilities of congenitally blind patients after surgery were found to be limited to the discrimination of elementary stimulus components (Jennerod, 1975). In two case reports, Carlson and Hyvärinen (1983) and Carlson, Hyvärinen, and Räinen (1986) reported different recovery rates of visual function. In the first case, a slow but continuous recovery of visual functions was observed, whereas in the second case, although some recovery appeared during 1 year of rehabilitation training, quality of vision was not sufficient to be useful in the patient's everyday life. Moreover, the patient never managed to master the labyrinth test and had difficulties in a visual–manual coordination task. Both poor visual acuity and alterations to spatio–cognitive processes may have interacted to account for poor spatial performance in born-blind but operated on patients. These data are in agreement with von Senden's (1960) observations, but, unfortunately, spatial abilities have not been tested in any study of early blind patients whose blindness was surgically alleviated in adulthood.

**Conclusion**

Altogether these data suggest a critical and irreversible effect of early lack of vision at the level of brain function. That the functioning of the occipital and some associative areas is modified in early blind people leads to the conclusion that nonvisual spatial information appears to be processed in brain systems in a different way in early blind than sighted people. This conclusion stands in contrast with the discrepant data obtained through the behavioral approach. Therefore, the possibility should not be excluded that some participants are able to compensate for their deficits by implementing specific strategies to cope with the difficulty of spatial tasks. Widely differing degrees of functional
recovery, depending on a participant’s cognitive abilities, motivation, educational level, and so forth, are frequently observed in neuropsychological studies. Brain damage of similar extent and origin, in exactly the same location, may induce extremely diversified deficits, on the basis of individual patients’ profiles. Although this issue has never been directly addressed in neuropsychological studies, it may account for the discrepant data obtained in early blind participants.

Possible Factors Accounting for the Discrepant Data

Among the factors likely to account for these controversial results, one can make a distinction between those related to the proper design of the experiment and those related to individual characteristics of the participants. Of course, some criteria used in the choice of the participants are well defined and form part of the methodology. These unambiguous criteria are considered, along with the other experimental variables in the design. However, the threshold between controlled and uncontrolled factors is rather vague. For instance, it is impossible to standardize precisely the method by which a participant’s history is evaluated. Nevertheless, it is not far fetched to imagine that aspects of history have some influence on performance in several tasks. To further complicate the situation, some researchers consider individual features (e.g., the origin of blindness) as experimental factors (independent variables), whereas others do not. Similarly, the age limit between early and late blind participants differs widely among studies. In this section, we examine, on the one hand, the alternative methodologies commonly reported in the literature and, on the other hand, some other variables that are less frequently controlled but may be of importance with regard to data interpretation.

Experimental Factors

In most of the cases, spatial memory tasks do not reveal differences between early (or congenitally) blind, late blind, and blindfolded sighted participants. In addition, in both spatial memory and inference tests in manipulatory space, the performance level of the congenitally or early blind participants was seldom impaired. However, as underlined above, different forms of spatial processing seemed to be used in manipulatory and locomotor space (see Barber & Lederman, 1988). In only one study did researchers reveal a difference between performance recorded in both spheres of space, no matter which type of test was used, spatial memory or inference (Fletcher, 1981b).

Early blind participants are often found to be impaired in ambulatory inference tests. It should be emphasized that inferential tasks are more difficult than only spatial memory ones, even for sighted participants (e.g., Rieser et al., 1986). The relative ease of spatial memory tasks does not appear to favor the emergence of an impairment in early blind participants, but the increased difficulty of inferential tasks might be expected to render spatial processing in these tasks more vulnerable to the interaction of various experimental and individual factors.

Consider first the scale of the situation. We have already pointed out (in Use of Symbolic Representations) that using a tactile map or a small-scale model appears to facilitate early blind participants’ ability to make inferences when they are tested in the actual situation. Ochaita and Haeritas (1993), comparing the performance of congenitally and late blind children, using large and small experimental layouts, reported that size was not an important factor. In most studies, however, when the experiment took place within a large environment, such as a neighborhood, early blind participants made more errors in direction estimates (Byrne & Salter, 1983; Dodds et al., 1982) during inferential tests. Therefore, one conclusion is that the spatial processing of large areas is facilitated by small-scale models of the situation in comparison with the locomotor exploration of the actual environment.

Whereas the few data obtained in large environments are rather convergent, discrepant results have been obtained when the experiments have been conducted in a room. On the one hand, no differences have been found between the three populations studied (Klatzky et al., 1995; Loomis et al., 1993; Worochel, 1951), and the early blind child observed by Landau (1986) was able to take shortcuts. On the other hand, important deficits were observed in early blind participants (Herman, Chatman, et al., 1983; Rieser et al., 1986; Veraart & Wanet-Defalque, 1987) during inferential tests. No conclusion can be drawn from these discrepant data unless there are experimental variables that are unique to testing within a small space and that may explain the observed divergences. During inferential tests in the locomotor space, early blind participants’ impairment was more frequently observed when the number of items to process was high (see Table I). Obviously, wide differences among the numbers of to-be-remembered items placed variable demands on memory and attention.

On the basis of the number of items to process, the nature of the response to make appears to play a role. This has been shown in relation to the localization of a sonorous target (see Stimulus Localization; Haber et al., 1993). Verbally estimating directions and distances, pointing with the finger, walking, orienting the body toward the target, drawing maps, and constructing models of the situation are different means participants have used to express spatial knowledge. For each type of externalization, specific mental computations of the spatial representation are required (Siegel, 1981).

When the experimental situation does not involve a large number of places, the participants are almost always required to walk. However, when many responses are required, this type of response would inordinately lengthen the duration of the experiment. In such situations, the mode of externalization usually involves the participant pointing toward the target places. Therefore, the two factors—the number of items to process and the nature of the response—are nearly always confounded (a large number of items and pointing vs. a small number of items and walking). Consequently, the contributions of each of these two variables are impossible to separate. Obviously, the interaction between the number of items and the nature of the required response could account for early blind participants’ deficits in inferential tests within a room. A fortiori it is understandable that when experiments not only involve a large number of places and landmarks that have to be localized by pointing but also take place in a large environment, significant deficits are found in early blind participants (Byrne & Salter, 1983; Dodds et al., 1982).

The level of familiarity with the experimental layout appears...
to play some role, although not as a determinant of the blind participants' performance. For example, in a highly familiar environment, it is likely that all possible routes have already been taken by the participants. Rieser et al. (1986) replicated the experiment from *Inferential Abilities* in a highly familiar environment. In that case, the early blind participants succeeded by using what Rieser et al. called inferential strategies. The participants claimed to have been helped by the fact that they had frequently had the opportunity to travel along all possible routes before the test. Accordingly, the designation of this task as inferential is somewhat inaccurate when conducted in a familiar environment because, as soon as a test involves previously experienced pathways, it is no longer an inferential task but a spatial memory.

Conversely, among the data that did not reveal a specific spatial impairment in the early blind groups, some were obtained in unfamiliar environments (Dodds et al., 1982; Worchel, 1951). However, most of the experiments took place in situations which, although unfamiliar, involved simple and familiar geometrical arrangements, such as a triangle (e.g., Worchel, 1951; Klatzky et al., 1995) or square (Millar, 1981b). It is likely that the spatial properties of these patterns were known by the participants. Therefore, except for one participant in Dodds et al.'s (1982) study; the early blind participants' success in inferential and spatial memory tasks appears related to some extent to their having had some experience of the spatial properties of the situation. However, this effect is not clear cut and may also be related to the methods of education to which the participants have been exposed.

Among the other experimental factors, consider the mode, active versus passive, of collecting spatial information. Fletcher (1981b) compared free and guided exploration in an actual room and a small-scale model. She did not find any effect of exploration mode. According to other data obtained with active or guided acquisition (see *Spatial Performances of Blind Persons*), this factor does not appear to play a crucial role in determining the performance level.

Moreover, Rossetti, Gauthier, and Thinus-Blanc (1996) examined pointing accuracy toward proprioceptive targets displayed on a sagittal plane. They found that the main axis of pointing distributions obtained in the blindfolded sighted group was aligned with the target array for the 8-s delay but not for the 0-s delay. By contrast, the main axis was aligned with movement direction for early blind participants for both delays. These results suggest that the delay between memorization and test phases is an important factor to account for discrepancies between tasks. Indeed, distinct spatial representations on the basis of the delay could be involved.

Finally, two other experimental factors, which may account for some divergent data, are the size of the groups under study and the criteria for matching the participants between groups. When there is little interindividual variability, statistical comparisons can be made between small-sized groups. However, in many studies, participants belonging to the same group may have totally different performance levels. This is evident, for instance, in the study carried out by Herman, Herman, et al. (1983). In general, interindividual variability appears more pronounced in blind than sighted populations (Heller, 1991; Heller & Kennedy, 1990; Hollins, 1989).

This problem of heterogeneity is closely related to the constitution of the groups and the matching of the participants across the populations studied. A reliable criterion of selection, which is sometimes but not always applied, is the measurement of IQ. Gender and hand predominance (for a discussion about the latter factor, see Lityerah, 1993) are other factors that are seldom taken into account when groups are selected. Another feature for matching participants across groups is the evaluation of their sociocultural level, assessed on the basis of type of job and level of education (Fletcher, 1981a; Hollins, 1989; Passini, Proulx, & Rainville, 1990; Warren, 1984; Warren, Anooshian, & Bollinger, 1973). Such an evaluation is easy to make on the basis of standardized criteria, but this kind of individual feature is prone to interact with others (see *Individual Factors*), which are also difficult to quantify.

In conclusion, it appears that many experimental factors can account for the discrepant data. Two of them are the size of the samples and the criteria for matching the participants between groups. Unfortunately, it appears difficult to assess their weight in the results discussed above. Other factors, such as the size of the experimental situation, type of response, and number of items to process, covary as a function of the experimental situation. For instance, in a room, there are a few items to process; the required response often consists of the participant walking to the target places. Consequently, it is difficult to precisely assess their respective roles, and further systematic studies are needed to enlighten psychologists of this issue.

**Individual Factors**

These factors are related to the history of the participants: age and origin of the onset of blindness, methods of education, affective reactions to the onset of blindness, and so forth. The precise role of these factors is extremely difficult to evaluate and control for when researchers are designing experiments and selecting participants. However, they may interact with the aforementioned experimental variables. Despite this, only a few researchers refer to their possible effects. Loomis et al. (1993), for instance, accounted for the divergent results that they obtained in exactly the same experimental conditions as those used by Rieser et al. (1982, 1986) in terms of individual differences and participant selection bias.

We next examine the individual features that appear likely to interact with task difficulty. Our aim is not to attempt to account for the divergent data in this way but rather to draw attention to their importance and emphasize the need to take such factors into account in future studies.

Concerning the origin of blindness, Loomis et al. (1993) found that the worst performing participant was congenitally blind with retrolental fibroplasia, yet Dodds, Hellawell, and Lee (1991) found no association between retrolental fibroplasia and spatial performance. However, relationships between the origin of blindness and performance level have never been subjected to systematic investigation.

Affective development appears to be influenced by early blindness. For instance, congenitally blind individuals are more likely to develop autism and stereotyped behavior patterns than sighted individuals (Janson, 1993). Moreover, the affective sequelae of blindness vary according to the age at which vision
is lost and whether the loss is sudden or progressive. Sudden onset of blindness often leads to depression. The participant does not develop the positive frame of mind that strengthens the efficacy of family care and effectiveness of rehabilitation methods (Hollins, 1989).

Another important factor is the age criterion determining the designation of participants as late blind. This varies among researchers. Classically, a person is considered congenitally blind if he or she has lost visual abilities during the first 3 years of life. Millar (1979), for example, has considered in her various studies only those participants who were blind from birth or have lost their sight before 20 months old, whereas Veraut and Wanet-Defalque (1987) and Rieser et al. (1986, 1992) included in their early blind groups participants who lost their sight at as late as 3 years old. For Herman, Chatman, et al. (1983) and Hatwell (1985), the limit of early blindness is the end of the first year of life. Moreover, the detection of blindness or visual impairment is rather difficult in babies, and, in many cases, visual impairments have evolved over time. This criterion is fundamental because vision plays an important role, if not crucial, in the development of sensori-motor coordination. This role culminates when autonomous locomotion is set up. Therefore, depending on the age threshold adopted by the researchers in splitting the blind population into early and late blind groups, variable data are likely to be found.

An additional factor related to that discussed earlier is the education to which congenitally blind participants have been exposed during childhood. Overprotective family attitudes may lead to a kind of movement limitation in early blind children, which may minimize their understanding of space (Heller, 1991; Jones, 1975). In specialized institutions for blind people, education is usually conducted at two distinct levels. The primary level concerns the organization of the body schema (left and right differentiation, postural adjustments, etc.). One can suppose that the variability across the educators, institutions, and countries is limited in view of the basic level to which such training is addressed. However, we know from our experience and from the literature that there are wide variations among the methods used in proper locomotor training. For instance, Hill et al. (1993) accounted for within-group heterogeneity in terms of the O & M methods with which blind participants have been instructed. In the United States, two types of familiarization methods are used to acquaint blind participants with novel areas (Hill & Ponder, 1976). The first method involves a guided and systematic exploration of the layout. In contrast, the second method, participants are provided with general rules related to how they should systematically explore novel environments. They have to implement these rules without actually being instructed. Independent of standardized education programs, autonomous locomotor training may be based on route learning (i.e., learning a sequence of specific landmarks) or alternatively some educators may give priority to teaching abstract spatial concepts.

An additional aspect, which should not be ignored, is that the construction of the body schema and sensori-motor adjustments have differing developmental time courses in sighted and blind people. Early blind toddlers’ specific motor reactions and locomotion are delayed, although postural evolution is otherwise similar to that observed in sighted babies. The blind baby stands upright unaided at about 14 months and starts moving independently 8 months later (Egan, 1979). The fact that, in a simple locomotor task, Portalier and Vital-Durand (1989) found that congenitally blind children need more time to complete a path previously walked than sighted children can be a consequence of a delayed occurrence such as the setting of sensori-motor coordination.

Ochatia and Huertas (1993) reviewed data on the development of sensori-motor and spatial cognition in congenitally blind participants. On the basis of their review, supplemented by their data, they concluded that blind adolescents fully develop their spatial representational ability later than sighted adolescents, that is, at about Age 17 (instead of Age 14 in sighted adolescents). This delayed development may account for deficits in congenitally blind participants tested before reaching Age 17 (Herman, Herman, et al., 1983).

In conclusion, it can be reasonably asserted that all of the factors related to an individual's history potentially contribute to the wide interindividual variability frequently encountered in groups of blind participants. That is the reason why the size and matching of groups represent such important experimental considerations and, in particular, why data interpretation could be biased in small-group studies (Hill et al., 1993; Loomis et al., 1993). These individual characteristics are likely to interact with the experimental factors discussed above. Among the experimental variables, the most vulnerable level of spatial processing involves abstract and complex mechanisms, such as inferences.

Toward a New Approach to Blind Persons’ Spatial Deficits

Because of the various possible interactions among the host of factors reviewed above and the complexity of the mechanisms involved in spatial processing, it appears difficult to draw definite conclusions about the effects of early blindness on spatial performance on the basis of the available literature. In this section, we propose an approach that we expect to lead to more definite conclusions, based on the analysis of the means or strategies spontaneously implemented by participants in becoming acquainted with their environment and solving spatial problems.

Qualitative Aspects of Behaviors and the Study of Strategies

Nobody would deny that there is usually more than one way to solve a task; any one of several alternative strategies may lead to a given performance level. Conversely, the same method of processing spatial information can lead to different performance levels. As an example, the simple recording of errors of place localization may lead to a conclusion that blind participants’ spatial abilities are similar to or worse than those of sighted participants. However, from these data alone, we cannot ascertain whether the same type of spatial processing is being adopted by the three populations or determine the exact nature of the impairment when the performance is found to differ between early blind and sighted groups. The latter issue is usually tackled by one conceiving various experimental situations that
dissect performance further and allow for a better understanding of the underlying cause of the observed deficit.

As long as there is a convergence among a large number of studies, one can be satisfied with this approach, which is in general use. However, we have seen from the review above (Spatial Performances of Blind Persons) that, where early–late blind comparisons are concerned, a consensus is far from our grasp, at least for tests for inferential processes. In such cases, some additional information is required to better understand the significance of the behavioral findings and the reasons of their divergence. We propose that this additional information may be accessed by studying the strategies used by the participants to get acquainted with their environment and solve spatial tasks. In other words, how does a participant reach an observed level of performance?

Measurement of latencies can be taken as a rough indicator of underlying processes (Kerr, 1983; Marmor & Zaback, 1976; Passini et al., 1990; Rieser et al., 1986), but it does not tell us if the observed data reflect quantitative or qualitative differences in spatial processing. Asking participants at the end of the task what they “had in their mind,” how they managed, and what information they relied on to perform the task can be helpful to understand the form of the spatial memory content and its capacity. Herman, Herman, et al. (1983), however, cautioned that verbal reports can be of limited value for understanding the nature of the cognitive processes that underlie task execution, particularly because visual words may be given different referents and significance by sighted and early blind people (Heller, 1991).

Other spontaneous behaviors (hesitations, remarks while performing the task, head movements, etc.) can also be recorded and quantified, although they are generally considered of ancillary interest—all the more so if the experiments have not been conceived to encourage their emergence. The participants’ degree of freedom is often reduced as much as possible to prevent uncontrolled factors from interfering with standardized conditions. These spontaneous behaviors, however, are observable expressions of the means that they had used to collect the information and significance by sighted and early blind people (Heller, 1991).

From these remarks, we propose that the study of blind people’s spatial competences should be tackled in three steps. The first step is to determine whether a variety of behavioral regularities can be observed and precisely defined in both blind and sighted participants. The second step is to determine whether correlations between behaviors and performance levels should not be underestimated as a methodology, although it is possible to establish a correlation between one strategy (or a set of strategies) and a performance level has no explanatory value of itself. What is necessary, in a further stage, is to attempt to find out the mechanisms that underlie these behavioral regularities.

Spatial Representations as Organizing Principles of Information Processing

From these remarks, we propose that the study of blind people’s spatial competences should be tackled in three steps. The first step is to determine whether a variety of behavioral regularities can be observed and precisely defined in both blind and sighted participants. The second step is to determine whether correlations between behaviors and performance levels can be found. If such correlations are found—as they were in Hill et al.’s (1993) experiment—then it appears legitimate to use the phrase “strategies for processing spatial information” to describe the observed behavioral regularities. A final, third step is to attempt to work out from the fine analysis of the strategies the actual mechanisms that underlie their behavioral expression.

Provided that the prerequisites above are met (i.e., strategies
are defined and correlated with performance levels), some aspects of the acquisition, organization, and use of spatial information specifically result in the construction of spatial representations, whose properties (plasticity, adaptive value, etc.) are those classically attributed to maplike representations.

On the basis of the data that we reviewed in Spatial Performances of Blind Persons, it may be expected that specific nonoptimal strategies are implemented by participants whose performance level is low in complex computations (inferential tests, e.g.). Those nonoptimal strategies may nonetheless lead to a good level of performance in relatively simple tasks, such as spatial memory tests. Conversely, optimal strategies should be observable, even when participants who succeed in tests of inference perform spatial memory tasks. Used alone, spatial memory tasks would not be difficult enough for differences among early blind and sighted people to become apparent.

Concerning the extrapolation to underlying mechanisms from the observation of strategies, consider the sole concrete example of this approach published so far, that is, Hill et al.'s (1993) experiment. It was observed that the best performers, regardless of whether they were early blind, late blind, or sighted participants, made both large exploratory cycles along the periphery of the experimental room and many back-and-forth movements between pairs of locations. The first pattern of activity may be taken as corresponding to the learning of the overall configuration of locations and of its topological features, whereas the second pattern would correspond to precise estimations of distance and angle relationships between the various places.

We have obtained preliminary data that converge with this interpretation (Gautet & Thinus-Blanc, 1996, in press). In these experiments, objects were displayed either in manipulatory or locomotor space (Figure 4). After a phase of spontaneous exploration, a spatial change was made to the object arrangement. Participants had to detect by exploring and verbally identify the modification. In addition to the number of correct responses, the patterns of exploration that participants spontaneously implemented to get acquainted with the various object configurations were recorded and analyzed.

In most of the cases, early blind participants made more errors than both late blind and blindfolded sighted groups. More important, we have found two types of patterns of exploration (Figure 4). The first type ("cyclic" patterns) consisted of visiting a sequence of objects, with the same one beginning and ending the cycle. The second type (back-and-forth patterns) was characterized by repeated trajectories between two places, as shown in Figure 4. The early blind participants used more cyclic patterns and less back-and-forth patterns than sighted participants. In addition, significant correlations were found between the performance level and the predominant use of systematic patterns of exploration; whereas the predominant use of cyclic patterns led to poor performance levels, optimal scores were obtained when participants frequently made back-and-forth trajectories.

The coexistence of these two components (large exploratory cycles and back-and-forth movements) may be interpreted as corresponding to a strategy that consists of roughly to comprehend the whole situation and subsequently refine this knowledge through more detailed analysis. Indeed, this hypothesis could be tested by restricting participants to just one of the elements of this compound strategy and testing the predominant memorized features of each of the resulting representations.

In this respect, it may also be valuable to attempt to correlate not only the means of spontaneously collecting new information but also some behavioral variables at the moment when the task is solved. For instance, Loomis et al. (1993) recorded the shape of the trajectories made by participants in a triangle-completion task, but they did not find any differences between groups. Experiments of this kind may be difficult to design.

Another advantage of studying strategies is that it may allow for insight into the pre-existing schemata that control the organization of information gathering. Neisser (1976) emphasized this notion about the cognitive map, which he conceived of as an "orienting" schema, that is an active information seeking structure. Instead of defining a cognitive map as an image, I will propose that spatial imagery itself is just an aspect of the functioning of orienting schemata. Like other schemata, they accept information and direct action. (p. 111)

The main point of Neisser's theory, with respect to this discussion, is that spatial representations or cognitive maps "direct" perceptual exploration. Thus, strategies should reflect some pre-existing organizing schemata. Although Neisser did not elaborate on how this control may be exerted, it is likely that well-constructed schemata do not direct exploration at random. General rules are likely to be implemented, so information is integrated along the general frame of the schema. Consequently, some of the general features of cognitive maps or other forms of representations should be deducible from the observation and analysis of investigatory behaviors.

Note that the term cognitive maps suggests or implies representation of a variety of specific environments, and this should be distinguished from the term schemata, which refers to a more abstract system of rules for information processing, applicable to any kind of spatial situation. However, simpler means of encoding information, such as the integration of body rotations, length of traveled paths (on the basis of speed and duration of travel), selection of particular landmarks and their association with the responses to make when these salient landmarks are encountered, and so forth, also constitute a set of rules to get acquainted with the environment. Although they are more similar to "directions for use" or tricks than high-level encoding mechanisms, they are also generalizable to any kind of situation,

![Figure 4. A schematic representation of an experimental layout in manipulatory and locomotor space. A shows exploratory cycles; B shows back-and-forth exploration.](image-url)
even though they do not lead to the same kind of representation as the schemata. In this respect, the same dichotomy can be applied at this level as between schemata and maps: On the one hand, there is a set of simple rules to acquire spatial knowledge; on the other hand, the implementation of this set of rules results in specific representations or spatial memories, whose constituents and functional properties are different and, in difficult situations, less efficient than overall representations. Spatial memories, nevertheless, do contain spatial features in terms of instructions for following routes, for instance (“turn left when leaving home and then turn right at the first cross-road to reach the shop”) rather than in terms of the actual spatial properties (“the shop is in a northwesterly direction from home”) charted only on maps. These levels of processing are referred to as “simple rules” and spatial memories.

On the basis of these definitions, we propose a schematic picture (Figure 5) of the various observable and deducible constituent elements of spatial processing and of their interactions. On the one hand, a distinction is made between the phase of information acquisition and organization, and, on the other hand, that of externalization of the knowledge, at the moment of solving a task, for instance. In these two phases, one can find observable expression in behaviors that can be analyzed and quantified and may reflect the kind of strategy(ies) implemented by the participants.

Spatial behavior can rely either on an exocentered frame of reference (e.g., the use of overall representations or cognitive maps) or on an egocentered frame of reference (following a route or locating an object with respect to one’s body, e.g.). Whatever the underlying mechanisms (i.e., exo- or egocentered), the spatial behavior, that is, any basic movement that relies on some kind of spatial knowledge, is executed along a body referent. Even if the decision to make a right turn at a particular junction relies on an abstract, exocentered, maplike representation, the action itself is organized along a body referent. Therefore, we consider actions that take place during both acquisition and use of spatial information to belong to an egocentered sphere of space. Spatial memories constructed by implementing simple encoding rules also belong to this level (see above and the beginning of the article). Only overall representations, which are independent of the participants’ position, represent the level of exocentered encoding of spatial information (although their behavioral expression involves the use of a body referent during action).

The constituent elements charted in Figure 5 can be related by various kinds of interactions. We start from a new situation in which a participant is asked to get acquainted. Consider also that no instructions are provided as to the way to collect spatial information. Then, the participant’s spontaneous adoption of a means of acquiring spatial information can be observed at this level. On the basis of the rules implemented (controlled themselves by the schemata that the participant has in mind—Arrow

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**Figure 5.** A schematic representation of a two-level spatial processing (schemata and simple rules of encoding), with the possible interactions (arrows) among the observable and deduced constituents of the whole process.
1—or by simpler rules—Arrow 2), this investigatory activity leads to the construction of either a maplike representation (Arrow 3) or a simple spatial memory of the current situation (Arrow 4). Now consider that the participant is performing a spatial task, so the researcher can evaluate the nature of his or her knowledge. If the task is relatively simple and does not require a reorganization of the representation, the representation can either be in the form of a map or of a specific spatial memory; either results in a high-performance level (Arrows 5 and 6). It is possible that some features of the way the task is actually executed could reveal the use of a particular form of representation.

Unlike experimental conditions where, usually, the participant is not given feedback as to the accuracy of his or her responses, everyday-life situations provide more or less immediate information about the efficiency of spatial behaviors. Then, by trial and error, the specific representations, whether they belong to the maplike or spatial memory level, are modified on the basis of the consequences of the action (Arrows 7 and 8). Accordingly, the general rules of information processing (schemata and simpler rules) are modified as a function of the improvement of the specific representations (Arrows 9 and 10). In return, they may also improve some of the aspects of the specific representations not experienced, but, more important, they influence the means used to further collect and use information when the participant is next faced with a new spatial problem.

Some other kinds of interaction could be added to this already complex, dynamic sketch because both forms of representation are supposed to coexist in sighted people. In the absence of instructions as to the finality to acquire spatial knowledge, it is assumed that, as far as a participant's cognitive capabilities make it possible, the higher level of information processing is spontaneously and systematically implemented during the very first exposure to a new environment. Later on, the use of maps would come into play only when necessary. In the case of a route traveled repeatedly, from home to office, for instance, we do not need any map of the district we go through; but if an unexpected event prevents us from taking the usual path, then we may need to recall an overall representation to be able to reach the office by taking another less familiar path, which we refer to as "making a detour." In addition, it is probable that, in participants without any impairment, there are interactions between the two levels of spatial processing. The information (kinaesthetic and vestibular feedback and stimulus–response [S–R] associations), which is collected on the basis of simple rules, may contribute to the refinement and precision of maps by providing them with spatial features (such as metric properties, e.g.) that can be processed step by step and independently from abstract schemata. Conversely, schemata may mediate a more advantageous organization and selection of kinaesthetic information and incorporate S–R associations. These issues refer to the hierarchical organization of spatial (and nonspatial) processing, which involves various levels of complexity, and to the interactions between them. A further discussion of this problem would go beyond the scope of this article. For the sake of clarity, we have considered only two levels, which find their justification in the distinction between experiments on spatial memory and those on higher level processing (inferential processes, mental transformation, etc.), but one should keep in mind that such a sharp dichotomy may need ultimately to be broken down into more subtle levels (see, e.g., Siegel & White's, 1975, model and What Is It About Vision That Could Make Its Role Critical?).

Conclusion

This hypothetical sketch of spatial information processing has several advantages regarding the interpretation of the equivocal evidence obtained on early blind persons' deficits.

First, we have concluded from the review of the literature that the onset of blindness usually has a minor impact on the completion of spatial memory tests. The observation of strategies in the preliminary phase—when the participant spontaneously acquires the information—should have a predictive value concerning the level of performance attained when that participant is subsequently tested on more complex tests.

Second, this approach begins to provide an answer to the following question: Is it possible to correlate specific strategies with the onset of blindness or are all the defined strategies equally distributed across the different groups? In the former case, if each population under study is characterized by one or several type(s) of strategy, the conclusion would be that experiencing (or not experiencing) early vision is a crucial factor that predominates over all others (individual features, e.g.) and that no consistent improvement should be expected from any kind of specialized education. In contrast, in the latter case, history and individual factors would have a powerful influence on the development of spatial competences and, more important, on the implementation of some types of strategy. This suggests that observed deficits are not irreversible and can be compensated for. In this respect, single-case or small-sample studies of individuals, whose history has been documented in detail, may be as important as group studies, assessing average performance, for teasing apart the roles of vision and other factors in spatial development.

The third point is in-line with this issue (the reversibility of the deleterious effects of early visual deprivation). Once optimal strategies (i.e., those associated with the highest performance levels) have been identified, can they be learned by the worse performers, in particular, by the early blind participants who had implemented nonoptimal strategies? Does this learning result in an improved performance level? Is the origin of the deficits an incapability to construct abstract schemata or merely to use them efficiently? These questions refer to Millar's (1994) distinction (see the beginning of this article) among ability, competence, and performance.

As we have already emphasized, these questions not only have important implications at a theoretical level (determining whether, e.g., there is a sensitive or critical period of the development during which visual experience plays a crucial role in spatial processing) but also may be of interest in relation with the selection and development of O & M training methods.

In view of the many possible combinations of strategy and performance levels, several patterns of results are likely to be exhibited after the worst early blind performers have been trained to use optimal strategies. Differing histories of individuals should be taken into account. If some congenitally blind participants (even a tiny minority) can learn to develop optimal
spatial abilities, then detailed studies of their development may suggest promising avenues for enhancing the development of all blind people. This approach is likely to lead to more reliable conclusions about the reversibility or otherwise of effects due to lack of visual experience than the sole comparison of performance levels.

In other domains, such as arithmetic learning in children, methods based on the study of strategies have been used with notable success. For instance, Siegler and Crowley (1994) showed that children can use their conceptual understanding to accurately evaluate strategies that they not only do not use yet but also are more conceptually advanced than the strategies they do use. A key factor enhancing strategy efficiency appears to be understanding goals and causal relationships. This idea could be applied to adults when teaching optimal strategies for processing spatial information.

Moreover, besides the specific study of blind people's spatial performances and competences, the analysis of other more general cognitive abilities involved in spatial processing should not be neglected to better understand, through the use of complementary approaches, the nature of the observed deficits. Some of these studies have already been undertaken, such as the determination of visual imagery capabilities (see What Is It About Vision That Could Make Its Role Critical?) and memory capacity (Cornoldi et al., 1991). Another field of investigation that so far appears neglected is the analysis of the specific features of spatial descriptions. A few studies of this type have already been conducted with blind participants (see, e.g., Brambring, 1982). It would be of major interest to examine this aspect in early blind persons. For instance, do the prepositions “in front of,” “behind,” and so forth, have the same meaning in ambiguous cases, that is, when they do not refer to a person but to objects in the environment?

In conclusion, the difficulty posed by the nature of the various factors whose interactions result in deep spatial deficits in some blind participants (whereas others appear to compensate successfully for a lack of vision) is a serious one because it has both theoretical and practical implications. For these reasons, we consider that this issue deserves to be tackled through the use of as many means of investigation as possible. We propose that, besides the classical approach of exposing populations of blind and sighted participants to various tests of their spatial performances, the means spontaneously implemented by the participants when first acquainted with the experimental situation and while they are performing the task should also be the object of quantitative studies. This approach, together with the investigation of general cognitive abilities (memory, mental imagery, and language), should contribute to the clarification of the exact nature of early blind persons' spatial deficits and confirm or invalidate the existence of a critical period in development during which vision might play the role of a genuine spatial sense.

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THINUS-BLANC AND GAUNET


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