Comparing the Effects of Congenital and Late Visual Impairments on Visuospatial Mental Abilities

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Abstract: This study compared participants who were congenitally visually impaired and those who became visually impaired later in life in a spatial memory task. The latter showed less efficient visuospatial processes than did the former. However, these differences were of a quantitative nature only, indicating common cognitive mechanisms that can be clearly differentiated from those of people who are congenitally blind.

Many experimental and neurophysiological investigations have addressed the nature of mental representations in people who are blind (see, for example, Byrne & Salter, 1983; Cohen et al., 1997; Herman, Chatman, & Roth, 1983; Hollins, 1989; Marchant & Malloy, 1984; Röder, Stock, Bien, Neville, & Rösler, 2002; Thinus-Blanc & Gaunet, 1997; Vanlierde & Wanet-Defalque, 2004, 2005; Vecchi, 1998). In addition, research has been directed to less severe forms of visual impairment and their effect on visuospatial abilities (see, for example, Vecchi et al., 2006).

According to the World Health Organization (WHO) (2001), the term *visual impairment* refers to both blindness and low vision. *Blindness* is defined as visual acuity of less than 10/200 or a field of vision that is constricted to (or less than) 10 degrees of arc around a central fixation in the better eye with the best possible correction. *Low vision* is defined as a maximum visual acuity of less than 20/63, but equal to or better than 10/200 or a corresponding loss of less than 20 degrees of the visual field in the better eye with the best possible correction. Visual impairment takes many forms and can be present in various degrees; scientific publications may differ in the criteria that are used to define a person who is blind as opposed to a person who has low vision.

In this article (as in Vecchi et al., 2006), we use the term *visually impaired* to refer to persons with low vision, who, after treatment or refractive correction, are capable of using vision to plan and carry out a task. According to our definition, people who are visually impaired are unable to read a newspaper from a typical viewing distance, even with the aid of eyeglasses or contact lenses, and usually rely on a combination of vision (although often requiring adaptations in lighting or the size of print) and other senses to learn.

There is experimental evidence to suggest that individuals who are visually impaired may perform better than may those who are congenitally totally blind and may resemble (or may even outperform) sighted persons in control groups in several spatial imagery tasks. For instance, Bigelow (1996) examined the development of spatial knowledge of the home environment of children who were sighted, visually impaired, and totally blind. The children who were totally blind had difficulty performing the task, especially when they had to rely on a straight-line distance criterion. In contrast, the children who were visually impaired and those who were sighted performed similarly, indicating that a reduced visual experience does not prevent the generation of an appropriate visual layout to be used to establish distances.

In other research, individuals who were visually impaired outperformed both those who were totally blind and those who were sighted and blindfolded in pattern-recognition tasks, such as the tactile embedded-figures test, Piaget's water-level task (which assesses haptic perception of the horizontal), and tactile recognition of the correct perspective in which a drawing is presented (Heller, Brackett, Scroggs, Allen, & Green, 2001; Heller et al., 2002; Heller, Wilson, Steffen, Yoneyama, & Brackett, 2003). The advantage of the people who were visually impaired was attributed to their reduced—but still present—experience with visual pictures and to their partially increased haptic skills (Heller et al., 2001, 2003). Similarly, Dufour and Gérard (2000) found that nearsighted participants, who had severe myopia for at least 10 years, performed better and faster than did sighted persons in a control group in a sound-localization task, indicating the occurrence of auditorily enhanced skills to compensate for the partial loss of sight. Blanco and Travieso (2003) reported that participants who were visually impaired performed more like blindfolded sighted participants than like participants who were totally blind in a task that required haptic exploration and mental scanning of a map. Finally, Vecchi et al. (2006) observed a similar performance in sighted people and those who were congenitally visually impaired in a spatial task that required the memorization of a number of locations that were presented on two-dimensional tactile matrices.

The performance observed in the people who are visually impaired can be associated with cerebral compensatory mechanisms that allow the cognitive system to work on the basis of reduced visual stimulation. When vision is absent, cortical areas that are usually devoted to processing visual information are recruited to elaborate stimuli that are delivered by other sensorial channels (see, for example, Cohen et al., 1999; Lanzenberger et al., 2001; Sadato et al., 1996, 1998). However, the extent of the cortical compensation is likely to vary according to both the extent and duration of blindness.

Some cortical compensation occurs in cases of low vision. For instance, Wolffe (1995) reported that a group of youngsters were capable of painting landscapes or still lifes as accurately as sighted people, despite a severe central field loss that was due to a dense central scotoma. Thus, in the presence of a central vision loss, the peripheral retina could convey fine details that are normally detected by the macula and fovea, allowing the visual cortex to

generate a clear, detailed representation of the visually presented external scenes. That is, the visual cortex can develop the ability to optimize and integrate the information that is received from all the receptors over the entire retina. Accordingly, Trauzettel-Klosinski (2002) found compensatory strategies that were related to high cortical plasticity in individuals who were affected by a central scotoma. However, the extent of the cortical compensation is likely to be inversely related to the extent of the visual deprivation.

Despres, Candas, and Dufour (2005) demonstrated that persons who are visually impaired use auditory cues to a different extent to position themselves in the environment, depending on the gravity of the visual deficit. They noted that even a small visual impairment (such as myopia) may cause compensatory plasticity phenomena. However, such compensatory phenomena are more pronounced in the case of total visual deprivation (Despres et al., 2005). In fact, people who were visually impaired (with only peripheral vision) performed worse than did those who were completely blind in generating a spatial map of the environment on the basis of an auditory stimulation (Lessard, Paré, Lepore, & Lassonde, 1998). Auditory compensation in persons who are blind is due to the recruitment of the deafferented sensory (visual) areas; in the case of low vision, these areas are still (although marginally) stimulated by their normal afferences; thus, plasticity phenomena are reduced (Lessard et al., 1998).

The extent of cortical reorganization phenomena is likely to be directly associated with the duration of the deficit. That compensatory mechanisms appear to be more robust in congenital than in late-onset blindness (Arno et al., 2001; De Volder et al., 2001; Hübel & Wiesel, 1977) accounts for the better performance of participants who are congenitally blind than of those with late-onset blindness in mental imagery tasks, indicating that early visual experience may not be so critical for enhanced spatial performance that is based on nonvisual cues (see, for example, Despres et al., 2005). However, several studies reported the superior performance of persons with late-onset blindness compared to persons who are congenitally blind, suggesting that prior visual experience is also critical for the development of spatial cognition (Büchel, Price, Frackowiak, & Friston, 1998; Fortin, Voss, Rainville, Lassonde, & Lepore, 2006; Gaunet, Martinez, & Thinus-Blanc, 1997; Gaunet & Rossetti, 2006; Heller, 1989; Heller et al., 2003; Imbiriba, Rodrigues, Magalhães, & Vargas, 2006; Vanlierde & Wanet-Defalque, 2004; Zuidhoek, Kappers, Noordzij, Van der Lubbe, & Postma, 2004). These discrepancies in the literature regarding a possible advantage of late-onset blindness over congenital blindness (or vice versa) in spatial imagery tasks may be due to different factors (familiarity with the task, the extent to which prior visual experience is involved, and so on; see Tinti, Adenzato, Tamietto, & Cornoldi, 2006, for a discussion).

Few studies have directly investigated the effect of the onset of a severe (but not complete) visual deficit on cortical organization (Baker, Peli, Knouf, & Kanwisher, 2005; Smirnakis et al., 2005; Sunness, Liu, & Yantis, 2004). Baker et al. (2005) found that areas of the visual cortex that are usually devoted

to processing foveal stimuli were activated by inputs in the peripheral vision of individuals with macular degeneration (diagnosed nearly 20 years earlier), indicating a large-scale reorganization of visual processing associated with this deficit. Conversely, Sunness et al. (2004) did not observe a significant plasticity in an individual with a partial macular lesion that was diagnosed 2 years before the test. An fMRI study conducted by Smirnakis et al. (2005) showed that the topography of the adult macaque primary visual cortex (V1) did not change after several months from an induced binocular retinal lesion (resulting in a binaular scotoma). Taken together, these studies suggest that in persons who are visually impaired, large-scale cortical reorganization may not occur until at least several years after sensory deprivation. The research by Despres et al. (2005) also revealed more efficient compensatory mechanisms in persons who were congenitally blind than in those with late-onset blindness.

To our knowledge, no study has directly investigated the nature and extent of possible differences in the cognitive abilities of individuals who become visually impaired (as opposed to blind) early in life versus those whose visual impairments occur later in life. In the study reported here, we required participants who were congenitally and late visually impaired to memorize a number of locations on a series of matrices to assess their ability to deal with complex configurations, to visualize three-dimensional stimuli mentally, and to integrate multiple inputs into a single representation. Earlier research showed that people who were congenitally visually impaired performed closer to sighted people than to blind people in a similar experimental paradigm (Vecchi et al., 2006) and that blindness determined specific difficulties in treating three-dimensional mental representations (Cornoldi, Bertuccelli, Rocchi, & Sbrana, 1993; Cornoldi, Cortesi, & Preti, 1991;Vecchi, 1998). Two different predictions may be formulated: (1) a better performance in individuals who are congenitally visually impaired than in those who are late visually impaired in visuospatial tasks as a function of stronger compensatory mechanisms that are associated with the congenital deficit or (2) a major role of prior normal visual experience that facilitates the generation of visuospatial mental representations in late compared to congenitally visually impaired persons. The presence of a residual visual experience offers the opportunity to test participants with both visual and tactile stimuli, allowing a direct comparison between mental representations that are generated on the basis of a different sensorial stimulation.

Some final observations on the participants' characteristics need to be specified. In the literature, many cutoff points have been adopted to define early blindness, ranging from a period of a few months to age 3 (Ungar, 2000). In this article, we use the term *congenitally visually impaired* to refer to individuals who were born with a visual impairment and the term *late visually impaired* to refer to individuals who had typical vision for their first 15–20 years of life. Also, it should be noted that all the participants in our research were matched for their ability to travel through familiar environments. This point is critical, since

previous research has suggested that spatial competence may depend more on an individual's skill in independent traveling than on prior visual experience (Loomis et al., 1993).

Method

Participants

The 32 visually impaired individuals who volunteered to participate in our study were all recruited from the same institute (the Ophthalmology Unit of Melegnano Hospital in Milan). Sixteen participants (7 men and 9 women) were congenitally visually impaired (mean age = 34, SD = 13.55) and 16 (7 men and 9 women) were late visually impaired (mean age = 41, SD = 7.89), with no significant difference in age across the groups, $F(1, 30) < 1$. In the late visually impaired group, the visual deficit had prevailed an average of 15 years before the study. The age of onset of the visual impairment ranged from 15 to 38 years. The extent of the visual impairment was confirmed by an appropriate staff member of the hosting institution. The participants' visual acuity was measured with the Standard ETDRS (Early Treatment Diabetic Retinopathy Study) visual acuity charts (logMAR). Best-corrected visual acuity in the better eye ranged from 0.5 logMAR to 1.6 logMAR (see Tables 1 and 2). A *t*-test on independent samples that was conducted on the participants' visual acuity (mean values were averaged between the two eyes) revealed that the two groups did not differ significantly in visual acuity ($p >$ .05). The visual field of each eye (that is, differential light sensitivity over the central and peripheral regions) was mapped with an automated perimeter Octopus 101, according to the standard clinical procedure for evaluating visual field loss. All the participants reported peripheral or central field losses or both (see Tables 1 and 2). This reduction in retinal sensitivity over the central and peripheral regions did not prevent any of them from perceiving the experimental stimuli.

All the participants were able to find their way around the area in which they lived (by walking or using public transportation). Moreover, as a part of the hospital therapy protocol, they all participated in rehabilitation and training programs. These programs were essentially directed to improve the participants' ability to use speech and optic devices (magnifying glasses and handheld magnifiers). The two groups were matched in terms of educational level. All the participants were capable of visualizing the experimental stimuli in the visual version of the task. Apart from their visual impairment, they were otherwise neurologically sound, and none reported tactile impairments.

Material and procedure

Two-dimensional (2-D) and three-dimensional (3-D) matrices were used, consisting of a number of wooden cubes each measuring 4 centimeters (about 1.6 inches) on each side. In particular, we used 5 x 5 2-D matrices and 3 x 3 x 3 3-D matrices. Within each configuration, either four or six target cubes were covered with black colored sandpaper that would be easily recognized both visually and by touch (see Figure 1).

The same stimuli were presented in two modalities: tactile and visual. The order of presentation of the two modalities was counterbalanced across the participants. In

Table 1
Participants with congenital visual impairments.

Participant	Sex	Age	Educational level and occupation	Etiology	VA	VF
1	M	60	University, engineer	Bilateral profound myopia	RE: 1.0 logMAR LE: 1.6 logMAR	Reduced central and peripheral sensitivity
2	F	37	High school degree, professional nurse	Albinism, bilateral strabismus, congenital nystagmus, and myopia	EE: 0.5 logMAR	Reduced central and peripheral sensitivity
3	M	21	University student	Bilateral hypermetropia, congenital glaucoma, strabismus (limited to RE)	RE: light perception LE: 0.7 logMAR	Reduced central and peripheral sensitivity
4	M	23	University student	Bilateral optic nerve atrophy owing to birth trauma	RE: no light perception LE: 0.7 logMAR	Reduced central and peripheral sensitivity
5	F	36	University student	Bilateral optic nerve atrophy	RE: 1.0 logMAR LE: 1.3 logMAR	Reduced central and peripheral sensitivity
6	M	55	High school degree, administrative clerk	Bilateral profound myopia	EE: 1.3 logMAR	Reduced central and peripheral sensitivity
7	M	22	University student	Bilateral cataract	RE: 0.7 logMAR LE: 1.0 logMAR	Reduced central and peripheral sensitivity
8	F	20	High school degree, unemployed	Bilateral cataract and glaucoma	RE: 1.0 logMAR LE: 1.3 logMAR	Reduced central and peripheral sensitivity
9	F	33	High school degree, administrative clerk	Bilateral retinitis pigmentosa inversa	EE: 1.5 logMAR	Reduced central and peripheral sensitivity
10	M	18	High school degree, unemployed	Bilateral optic nerve atrophy	RE: 1.6 logMAR LE: 0.7 logMAR	Reduced central and peripheral sensitivity
11	M	19	High school degree, part-time clerk	Bilateral congenital glaucoma	EE: 0.7 logMAR	Reduced central and peripheral sensitivity
12	F	45	High school degree, housewife	Bilateral profound myopia	EE: 0.9 logMAR	Reduced central and peripheral sensitivity
13	F	53	High school degree, housewife	Bilateral profound myopia	EE: 1.6 logMAR	Reduced central and peripheral sensitivity
14	F	30	High school degree, administrative clerk	Bilateral congenital cataract	EE: 1.0 logMAR	Reduced central and peripheral sensitivity
15	F	34	High school degree, administrative clerk	Bilateral congenital glaucoma	EE: 0.9 logMAR	Reduced central and peripheral sensitivity
16	F	38	High school degree/ administrative clerk	Bilateral congenital cataract	EE: 1.0 logMAR	Reduced central and peripheral sensitivity

Note: VA = visual acuity with the best correction (logMAR), VF = visual field, LE = left eye, RE = right eye, and EE = both eyes.

the tactile modality, the participants were blindfolded and were given 10 seconds to explore the matrices tactilely in order to memorize the target locations. In the test that immediately followed the memorization phase, the participants had to retrieve tactilely, on a series of corresponding blank matrices, the target cubes they had previously memorized by directly pointing to them with their (preferred) finger. They moved their hands smoothly across the matrix and stopped on the cell they believed to be a target; some also verbally indicated the target (by saying "this one" or "here") as well as pointing to it with a finger.

The visual modality procedure was identical to that used in the tactile modality, but for this task the participants were required to explore the matrices visually, not tactilely. In the test, the participants indicated the targets by pointing to them with a finger; some also verbally confirmed their choice. Before each individual experimental session, the capacity of the participants to distinguish the targets visually was checked by direct questions to the participants and by asking them to point to a couple of targets with their right index finger. No participant reported having any problem recognizing the targets.

There were four different experimental conditions: (1) the 2-D single matrix condition, in which the targets were presented on a single 2-D matrix (see Figure 1a); (2) the multiple matrices condition, in which the targets were equally divided between two simultaneously presented 2-D matrices and had to be retrieved on two corresponding blank matrices during the test (see Figure 1b); (3) the integration condition, in which the targets were presented equally divided between two different 2-D matrices but had to be indicated on a single matrix during the test (see Figure 1c); and (4) the 3-D single matrix condition, in which the targets were presented on a single 3-D matrix (see Figure 1d). Each condition consisted of eight trials in which the locations of the targets were varied. Two practice trials preceded each condition. The order in which the conditions were presented was counterbalanced for dimensionality (2-D and 3-D stimuli); in addition, within the 2-D tasks, single conditions were always presented first, and the order of presentation of the multiple and the integration conditions was counterbalanced. The entire experimental session lasted approximately 1.5 hours.

Results

The results are presented in Figure 2. The order in which the tactile and visual versions of the task were administered did not significantly affect the participants' performance, $F(1, 28) < 1$. An analysis of variance (ANOVA) was conducted to investigate the performance in 2-D matrices only and considered the between-subjects variable of group (congenital versus late visual impairment) and the within-subject variables of modality (visual versus tactile), condition (single versus multiple versus integration), and number of targets (four versus six).

Overall, the participants who were congenitally visually impaired outperformed those who were late visually impaired (mean correct = 67.41% versus 56.94%), $F(1,30) = 10.38$, $MSE = 10503.65$, $p < .005$. Moreover, for all the participants, accuracy was higher with the visual (mean correct = 66.90%) than with the tactile matrices (mean correct = 57.45%),

Table 2
Participants with late visual impairments.

Participant	Sex	Age	Educational level and occupation	Etiology	Years since onset	VA	VF
1	M	32	High school degree, painter	Retinitis pigmentosa	10	RE: 0.9 logMAR	Central 5 degrees
2	F	40	High school degree, professional nurse	Stargardt's disease	6	EE: 1.3 logMAR	Reduced central and peripheral sensitivity
3	M	26	High school degree, administrative clerk	Retinitis pigmentosa	5	EE: 0.7 logMAR	Central 5 degrees
4	M	40	High school degree, real estate agent	Retinitis pigmentosa	20	EE: 0.7 logMAR	Central 5 degrees
5	M	57	Primary school, retired clerk	Retinitis pigmentosa	30	RE: 0.9 logMAR LE: 0.7 logMAR	Central 10 degrees
6	F	44	High school degree, professional nurse	Retinitis pigmentosa	27	RE: 0.9 logMAR LE: 0.8 logMAR	Central $<$ 5 degrees
7	M	46	High school degree, Administrative clerk	Retinitis pigmentosa	23	EE: 0.7 logMAR	Central 5 degrees
8	F	38	High school degree, Administrative clerk	Glaucoma	5	EE: 0.8 logMAR	Reduced central and peripheral sensitivity
9	F	37	High school degree, Administrative clerk	Retinitis pigmentosa	12	RE: 0.7 logMAR LE: 0.6 logMAR	Central 5 degrees
10	F	39	High school degree, Administrative clerk	Retinitis pigmentosa	23	EE: 0.6 logMAR	Central 5–10 degrees
11	F	38	High school degree, Administrative clerk	Retinitis pigmentosa	18	EE: 0.6 logMAR	Central 5–10 degrees
12	M	34	High school degree, Administrative clerk	Retinitis pigmentosa	19	EE: 0.6 logMAR	Central 5 degrees
13	F	55	High school degree, retired clerk	Occipital hemorrhage	20	EE: 0.5 logMAR	Reduced central and peripheral sensitivity
14	M	48	High school degree, administrative clerk	Retinitis pigmentosa	10	EE: 0.7 logMAR	Central 10 degrees
15	F	43	High school degree, administrative clerk	Retinitis pigmentosa	10	EE: 0.6 logMAR	Central 10 degrees
16	F	41	High school degree/ Administrative clerk	Stargardt's disease	8	EE: 1.3 logMAR	Reduced central and peripheral sensitivity

Note: VA = visual acuity with the best correction (logMAR), VF = visual field, LE = left eye, RE = right eye, and EE = both eyes.

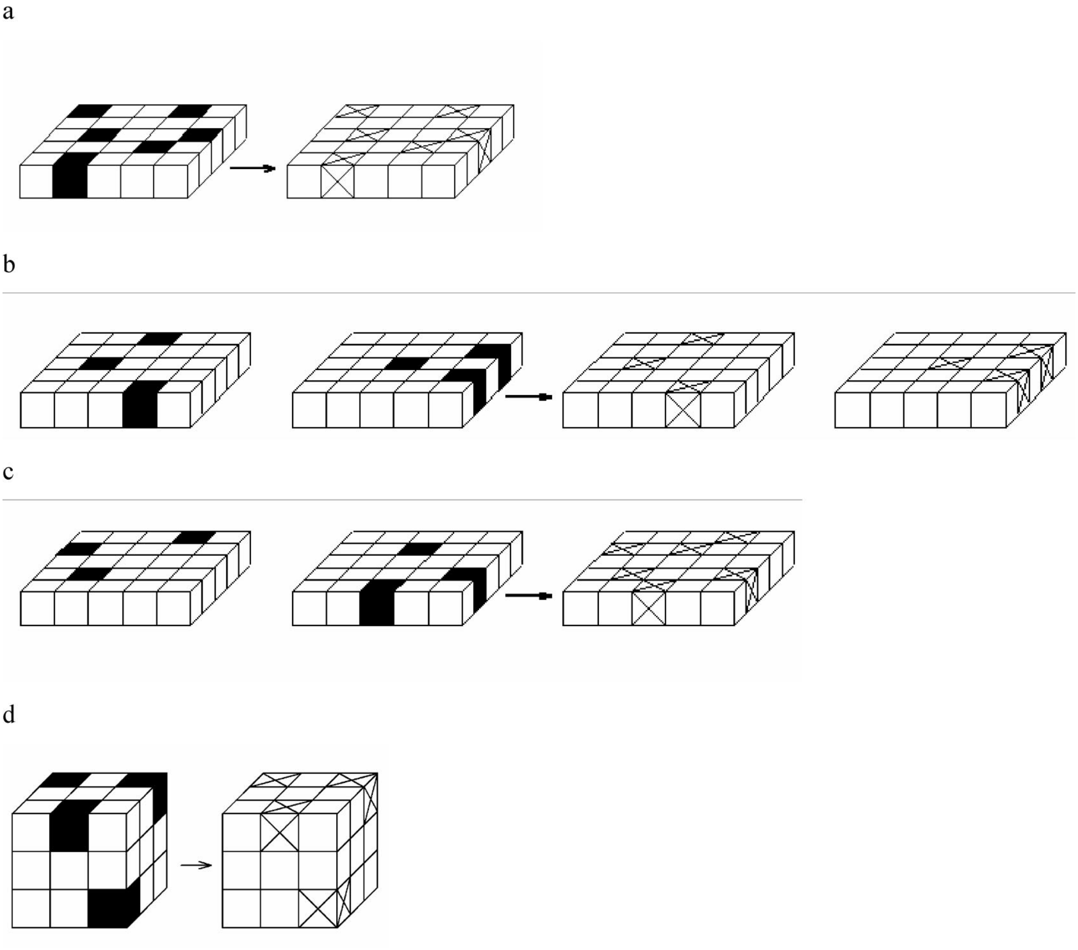
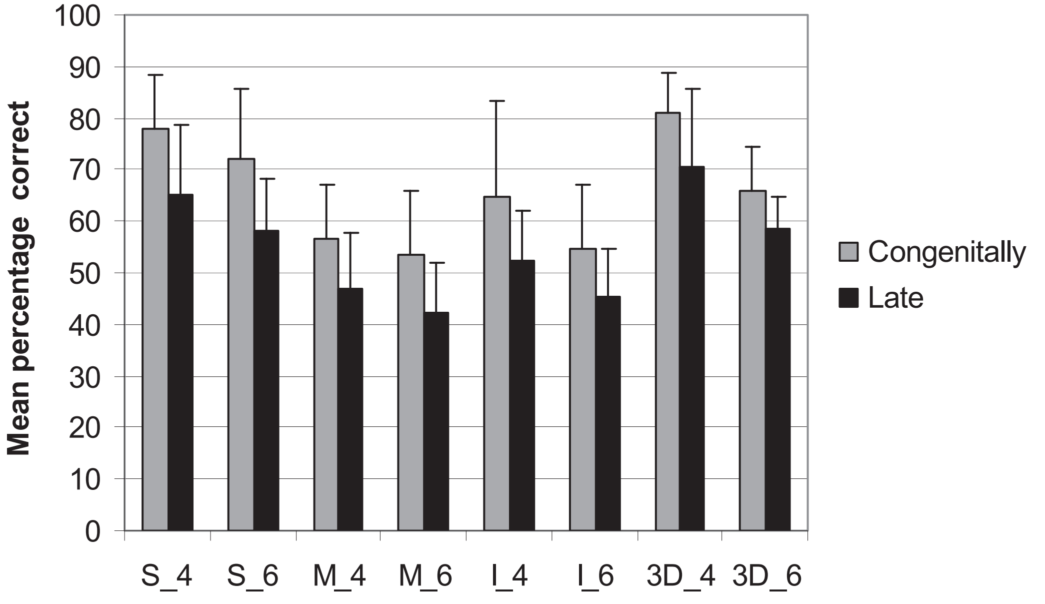


Figure 1. Example of matrices used in the tactile version of the task in the (a) 2-D single matrix condition (six targets); (b) 2-D multiple matrices condition (six targets); (c) 2-D integration condition (six targets); and (d) 3-D single matrix condition (four targets).

$F(1,30) = 67.16$, $MSE = 8555.09$, $p < .001$, and when four (mean correct = 65.63%) rather than six targets (mean correct = 58.72%) had to be memorized, $F(1,30) = 41.72$, $MSE = 4571.94$, $p < .001$. Condition was also significant, $F(2,60) = 72.43$, $MSE = 13872.92$, $p < .001$. Pairwise comparisons (Bonferroni adjustment for multiple comparisons was applied) revealed that the single matrix condition (mean correct = 73.84%) led to a better performance than did both the multiple matrices (53.84%), $t(31) = 11.45$, $p < .001$, and the integration conditions (58.84%), $t(31) = 8.76$, $p < .001$. Moreover, the participants performed significantly better in the integration condition than in the multiple matrices condition, $t(31) = 3.01$, $p < .01$. Finally, the condition significantly interacted with the number of targets, $F(2,60) = 5.03$, $MSE = 238.48$, $p < .001$, because the difficulty associated with the increasing number of targets was less evident in the multiple matrices condition. No other interaction was significant (see Figure 2).

a)



b)

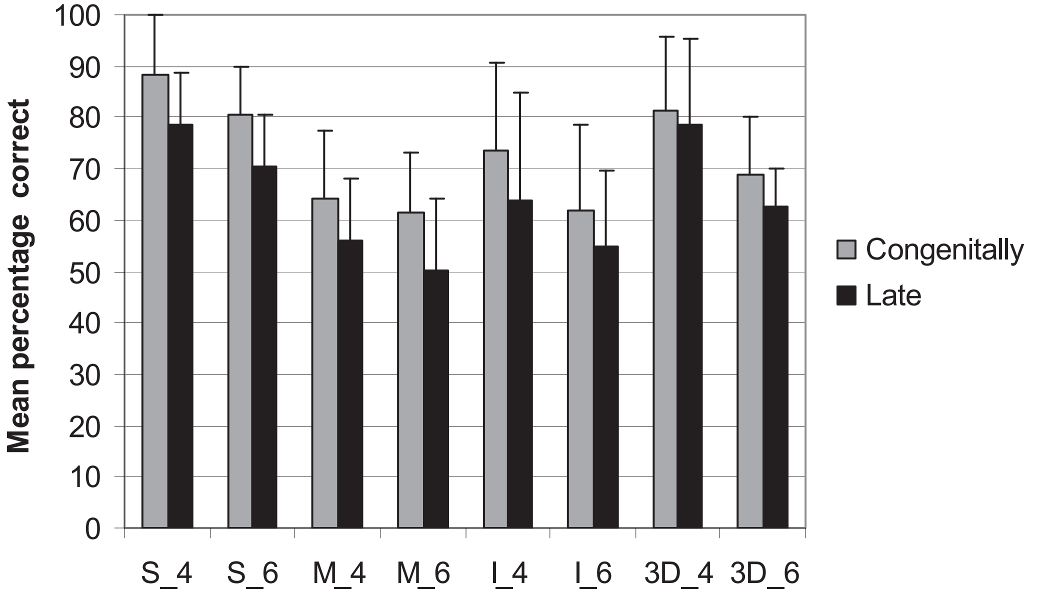


Figure 2. Mean percentage correct performance in the tactile (a) and the visual (b) modality for the 2-D single (S) matrix, 2-D multiple (M) matrices, 2-D integration (I) matrices, and 3-D single matrix conditions with four and six targets in participants with congenital and late visual impairments. Error bars depict standard deviations.

A second ANOVA was carried out to verify the effect of dimensionality (2-D versus 3-D) on the accuracy of spatial memory, taking into account the effect of modality (visual versus tactile). The analysis compared only the percentage of positions that were correctly retrieved in the single-matrix 2-D condition and the single-matrix 3-D condition (data obtained in the other two 2-D conditions—multiple and integration—were not considered). The visual modality was again easier than the tactile modality (76.14% versus 68.62%), $F(1, 30) = 40.65$, $MSE = 1809.39$, $p < .001$. The results also revealed a significant main effect of group, $F(1,30)=11.15$, $MSE=2677.44$, $p < .005$, indicating that the participants who were congenitally visually impaired outperformed those who were late visually impaired (mean correct = 76.95% versus 67.81%). Finally, although the main effect of dimensionality was not significant, dimensionality and modality significantly interacted, $F(1,30) = 9.42$, $MSE=410.29$, $p < .01$. Pairwise comparisons (a Bonferroni adjustment for multiple comparisons was applied) showed an advantage of 2-D matrices over 3-D matrices in the visual modality (79.40% versus 72.88%), $t(31) = 3.08$, $p < .005$, but not in the tactile modality (68.29% versus 68.95%), $t(31) = -.32$, $p > .5$.

Discussion

Having no vivid visual experience from birth, as opposed to loosing it after a number of years, has a different effect on visuospatial processes. This difference seems to be "quantitative," rather than "qualitative." In fact, the participants who were congenitally visually impaired performed better than did those who were late visually impaired when they were required to remember a number of locations that were presented on tactile or visual matrices, although the two groups' general pattern of performance was identical. We suggest that the better performance of the participants who were congenitally visually impaired compared to the performance of the participants who were late visually impaired depended on more developed compensatory mechanisms in the former group. These data are in line with previous research on individuals who are visually impaired (not blind) that has demonstrated that more efficient compensatory mechanisms are associated with the earlier onset of visual impairment (Baker et al., 2005; Smirnakis et al., 2005; Sunness et al., 2004). Other lower-level factors (different residual visual acuity and visual field and differences in mobility skills) may also account for the advantage of the participants who were congenitally visually impaired.

With regard to the etiology of the visual impairment and its effect on the visual field, retinitis pigmentosa was the main cause of visual impairment in the late visually impaired group, whereas nerve atrophy, glaucoma, and myopia were the main causes in the congenitally visually impaired group. Retinitis pigmentosa is usually accompanied by the loss of the peripheral visual field, while the central visual field can be relatively preserved. Conversely, the participants who were congenitally visually impaired had decreased sensitivity in both the peripheral and central visual fields. Thus, the two groups differed in both the age of onset of their visual impairments and their residual visual fields. However, we exclude

the possibility that the difference in performance in this spatial task was caused by the latter factor. First, a preserved central visual field is more important for this type of task than is a preserved peripheral field (the latter being more critical in navigational tasks). Overall, the participants who were late visually impaired had preserved central vision (with the exception of two individuals with Stargardt's disease) and hence should have outperformed those who were congenitally visually impaired.

Moreover, peripheral and tunnel vision led to a comparable performance in a study of the role of concomitant vision in improving haptic performance (Millar & Al-Attar, 2005). The task required the participants to memorize locations that were presented on a tactile map without vision, with concomitant full vision, with peripheral vision, with tunnel vision, or in a condition of residual diffuse light perception (by using particular spectacles). Millar and Al-Attar noticed that in the peripheral vision condition—thanks to appropriate head movements—the participants could count on an adequate (although blurred) view of the relevant stimuli. Similarly, in the tunnel vision condition, they were able to obtain a clear view of any area of the map by moving their heads appropriately. In fact, peripheral and tunnel vision do not determine differences in perception as long as participants are free to move their heads. In our study, the participants were free to move their heads, and none reported difficulty visualizing the matrices; on this basis, we exclude the idea that the differences between the congenitally visually impaired and the late visually impaired groups were visual field dependent. Taken together, our results and Millar and Al-Attar's suggest a marginal role for the residual field of view in static spatial memory tasks.

Furthermore, the participants who were congenitally visually impaired had reduced visual acuity (although not significantly reduced, $p > .05$) compared to those who were late visually impaired. Therefore, the advantage of the participants who were congenitally visually impaired over those who were late visually impaired is even more striking. Hypothesizing a role of visual acuity in determining the pattern of results that was obtained, one would expect that the higher the visual acuity, the better the accuracy in performing tasks (at least in the visual version of the task). However, this was not the case, and no interaction was found between group and task modality (visual versus tactile). Visual acuity does not seem to play a critical role in the performance of these tasks.

Another important factor to be considered is a possible difference in the mobility capacities of the two groups, since spatial competence may depend more on skills of individuals in traveling independently than on prior visual experience (Loomis et al., 1993). However, since all the visually impaired participants in our study were matched for their ability to travel independently in familiar environments, the observed differences between the two groups cannot be due to different skills in traveling independently (see Loomis et al., 1993). The advantage of the participants who were congenitally visually impaired may have depended on their longer practice in coping with their reduced visual experience, compared to those who were late visually impaired. However, the participants who were late

visually impaired had been visually impaired for many years (an average of 15 years), so that their level of practice with reduced vision should have been comparable to that of the participants who were congenitally visually impaired.

Finally, it may be argued that the advantage of the participants who were congenitally visually impaired over those who were late visually impaired depended on a more developed attentional mechanism. Indeed, previous research found that the attentional performance of participants who were early blind was greater than that of a matched control group of sighted participants, which suggests that greater attention compensates for the lack of vision by developing capacities in the nonvisual senses that exceed those of sighted people (Collignon, Renier, Bruyer, Tranduy, & Veraart, 2006). However, other research has demonstrated that attentional mechanisms—for instance, those that are involved in focusing auditory attention in the periphery—improve to a similar extent in persons with early and late blindness, although different cortical mechanisms seem to be involved in the two groups (Fieger, Röder, Teder-Sälejärvi, Hillyard, & Neville, 2006).

In line with the previous considerations, the most likely explanation for the advantage of the participants who were congenitally visually impaired over those who were late visually impaired is the development of more drastic compensatory mechanisms that are associated with a congenital deficit. Our data suggest that the brain capacity to function on the basis of a reduced visual percept is modulated by the timing of the onset of the visual impairment, as is the case with total blindness (Arno et al., 2001; De Volder et al., 2001; Despres et al., 2005; Hübel & Wiesel, 1977). Neuroimaging research by Sadato, Okada, Honda, and Yonekura (2002) showed that cortical reorganization is more efficient for braille reading when the blindness occurred before age 16, a critical time for a functional shift of the primary visual cortex from processing visual stimuli to processing tactile information. All the participants in our study who were late visually impaired became visually impaired after age 16; thus, according to Sadato et al. (2002), the extent of the cortical reorganization phenomenon was likely to be more pronounced in the congenitally visually impaired than in the late visually impaired group.

With regard to the pattern of performance, all the participants found memorizing targets on a single matrix (irrespective of its dimensionality) easier than remembering targets that were presented on two different matrices (the multiple and integration conditions). Moreover, the two groups were similarly affected by the increasing number of to-be-remembered targets that affected their overall performance. It is likely that the decrease that was observed both when stimuli were two distinct matrices (multiple and integration conditions) and when the number of targets increased was a direct consequence of the increased complexity of the configurational set, rather than of the presence of a visual deficit; similar effects were reported with sighted individuals who were tested on comparable tasks (Vecchi, Monticelli, & Cornoldi, 1995).

It is interesting that both groups performed better in the integration condition than in the multiple matrices condition.

Although the amount of memory load (input) was the same for the two conditions, the participants were aware that, in the integration condition, they had to retrieve all the target locations within a single matrix. In this type of situation, certainly the most effective strategy is to generate a novel representation in which all the target locations are included, so that one has to maintain a single representation instead of two. If maintenance is facilitated, the previous phase of generating the internal representation may require greater effort in the integration condition (in which two configurations are combined into a single representation) than in the multiple matrices condition (in which the mental representations are just copies of the original visual percept). In the case of sighted people, we do not necessarily expect an advantage of one condition over the other (possible advantages, in any direction, may be due to individual variables, such as age and gender, that have been found to be particularly sensitive to the active or operational processes that are required; see, for example, Cornoldi & Vecchi, 2003).

An advantage of the integration condition over the multiple condition is less surprising in a person who is visually impaired, since the visuospatial memory system of a visually impaired person is likely to develop an exceptional capacity to cope with missing information to generate coherent representations. Although the visuospatial system of a person who is visually impaired works on the basis of limited visual experience, previous studies have suggested that it may nonetheless generate appropriate internal representations of the external visual world (see, for example, Wolffe, 1995). The cognitive processes that underlie integration tasks are centered on operational mechanisms that are overdeveloped in people who are visually impaired; thus, they determine the better performance of tasks, such as integration matrices, that mainly tap into these functions.

Although the participants' overall performance was better with four than with six targets, this advantage was less pronounced in the multiple matrices condition than in the other two conditions. The capacity to generate a mental representation that exactly resembles the original input may be already overloaded with fewer targets in the multiple matrices condition (but not in the integration condition, which involves higher imagery processes), so that the increasing number of targets does not affect performance.

With regard to the dimensionality of the stimuli, we reported a general advantage of 2-D versus 3-D matrices in the visual modality, which was probably due to the visual deficit directly interfering with the acquisition of the visual stimuli. In fact, the participants who were visually impaired were not affected by the use of 3-D versus 2-D matrices in the tactile modality, whereas using 3-D mental representations is difficult for people who are blind (Cornoldi et al., 1991, 1993). If the mental representations of the participants who were late visually impaired appeared to be only quantitatively different from those of the sighted participants (see, for example, Vecchi et al., 2006), the limitations observed in the blind participants were more qualitative. In fact, the cortical mechanisms in a person who is blind develop mainly on the basis of touch and hearing, which allow for only a sequential encoding of the information; thus at a

higher cognitive level, the person has specific difficulties simultaneously maintaining multiple images in memory (see Vecchi, Tinti, & Cornoldi, 2004). It has been suggested that processing 3-D representations may involve the simultaneous maintenance of multiple views of the same image, which requires some sort of parallel processing (Vecchi et al., 2004). Accordingly, the maintenance of multiple information in memory was found to be impaired in the participants who were blind, while integration processes were relatively unaffected (Vecchi et al., 2004).

Finally, regardless of the effects that are directly dependent on the visual deficit interfering with the generation of visual images that are associated with the visual percept, the pattern of performance was otherwise identical across the visual and tactile modalities, suggesting the existence of supramodal cognitive processes. In fact, supramodal cerebral areas that are capable of processing information that is delivered by different sensorial channels have been identified (see Easton, Srinivas, & Greene, 1997; Pietrini et al., 2004; Stein & Meredith, 1993).

In conclusion, the findings of this study offer further insights into the ways in which cognitive processes develop in the presence of severe sensory loss. They have shown that the onset of visual impairment is consistently associated with the presence of compensatory mechanisms that allow the system to minimize the effects of reduced sensorial stimulation.

References

Arno, P., Vanlierde, A., Streel, E., Wanet-Defalque, M. C., Sanabria-Bohorquez, S., & Veraart, C. (2001). Auditory substitution of vision: Pattern recognition by the blind. *Applied Cognitive Psychology, 15,* 509–519.

Baker, C. I., Peli, E., Knouf, N., & Kanwisher, N. G. (2005). Reorganization of visual processing in macular degeneration. *Journal of Neuroscience*, *25,* 614–618.

Bigelow, A. E. (1996). Blind and sighted children's spatial knowledge of their home environments. *International Journal of Behavioral Development, 19,* 797–816.

Blanco, F., & Travieso, D. (2003). Haptic exploration and mental estimation of distances in a fictitious island: From mind's eye to mind's hand. *Journal of Visual Impairment & Blindness, 97,* 298–300.

Büchel, C., Price, C., Frackowiak, R. S., & Friston, K. (1998). Different activation patterns in the visual cortex of late and congenitally blind subjects. *Brain, 121,* 409–419.

Byrne, R. W., & Salter, E. (1983). Distance and directions in the cognitive maps of the blind. *Canadian Journal of Psychology*, *37,* 293–299.

Cohen, L. G., Celnik, P., Pascual-Leone, A., Corwell, B., Faiz, L., Dambrosia, J., Honda, M., Sadato, N., Gerloff, C., Catala, M. D., & Hallett. M. (1997). Functional relevance of cross-modal plasticity in blind humans. *Nature, 389,* 180–183.

Cohen, L. G., Weeks, R. A., Sadato, N., Celnik, P., Ishii, K., & Hallett, M. (1999). Period of susceptibility for cross-modal plasticity in the blind. *Annals of Neurology, 45,* 451–460.

Collignon, O., Renier, L., Bruyer, R., Tranduy, D., & Veraart, C. (2006). Improved selective and divided spatial attention in early blind subjects. *Brain Research, 1075,* 175–182.

Cornoldi, C., Bertuccelli, B., Rocchi, P., & Sbrana, B. (1993). Processing capacity limitations in pictorial and spatial representations in the totally congenitally blind. *Cortex, 29,* 675–689.

Cornoldi, C., Cortesi, A., & Preti, D. (1991). Individual differences in the capacity limitation of visuo-spatial short-term memory: Research on sighted and

totally congenitally blind people. *Memory and Cognition*, *19,* 459–468.

Cornoldi, C., & Vecchi, T. (2003). *Visuospatial working memory and individual differences: Essays in cognitive psychology*. Hove, England: Psychology Press.

De Volder, A. G., Toyama, H., Kimura, Y., Kiyosawa, M., Nakano, H., Vanlierde, A., Wanet-Defalque, M. C., Mishina, M., Oda, K., Ishiwata, K., & Senda, M. (2001). Auditory triggered mental imagery of shape involves visual association areas in early blind humans. *NeuroImage, 14,* 129–139.

Despres, O., Candas, V., & Dufour, A. (2005). The extent of visual deficit and auditory spatial compensation: Evidence from self-positioning from auditory cues. *Cognitive Brain Research*, *23*(2–3), 444–447.

Dufour, A., & Gérard, Y. (2000). Improved auditory spatial sensitivity in near-sighted subjects. *Cognitive Brain Research*, *10,* 159–165.

Easton, R. D., Srinivas, K., & Greene, A. J. (1997). Do vision and haptics share common representations—Implicit and explicit memory within and between modalities. *Journal of Experimental Psychology: Learning Memory and Cognition*, *23,* 153–163.

Fieger, A., Röder, B., Teder-Sälejärvi, W., Hillyard, S. A., & Neville, H. J. (2006). Auditory spatial tuning in late-onset blindness in humans. *Journal of Cognitive Neuroscience*, *18,* 149–157.

Fortin, M., Voss, P., Rainville, C., Lassonde, M., & Lepore, F. (2006). Impact of vision on the development of topographical orientation abilities. *NeuroReport*, *17,* 443–446.

Gaunet, F., Martinez, J. L., & Thinus-Blanc, C. (1997). Early-blind subjects' spatial representation of manipulatory space: Exploratory strategies and reaction to change. *Perception*, *26,* 345–366.

Gaunet, F., & Rossetti, Y. (2006). Effects of visual deprivation on space representation: Immediate and delayed pointing toward memorised proprioceptive targets. *Perception*, *35,* 107–124.

Heller, M. A. (1989). Picture and pattern perception in the sighted and blind: The advantage of the late blind. *Perception, 18,* 379–389.

Heller, M. A., Brackett, D. D., Scroggs, E., Allen, A. C., & Green, S. (2001). Haptic perception of the horizontal by blind and low vision individuals. *Perception, 30,* 601–610.

Heller, M. A., Brackett, D. D., Scroggs, E., Steffen, H., Heatherly, K., & Salik, S. (2002). Tangible pictures: Viewpoint effects and linear perspective in visually impaired people. *Perception*, *31,* 747–769.

Heller, M. A., Wilson, K., Steffen, H., Yoneyama, K., & Brackett, D. D. (2003). Superior haptic perceptual selectivity in late-blind and very-low-vision subjects. *Perception*, *32,* 499–511.

Herman, J. F., Chatman, S. P., & Roth, S. F. (1983). Cognitive mapping in blind people: Acquisition of spatial relationships in a large-scale environment. *Journal of Visual Impairment & Blindness*, *77,* 161–166.

Hollins, M. (1989). *Understanding blindness*. Hillsdale, NJ: Lawrence Erlbaum.

Hübel, D. H., & Wiesel, T. N. (1977). Functional architecture of macaque monkey visual cortex. *Proceedings of the Royal Society of London, Series B: Biological Sciences*, *198,* l–59.

Imbiriba, L. A., Rodrigues, E. C., Magalhães, J., & Vargas, C. D. (2006). Motor imagery in blind subjects: The influence of the previous visual experience. *Neuroscience Letters*, *400,* 181–185.

Lanzenberger, R., Uhl, F., Windischberger, C., Gartus, A., Streibl, B., Edward, V., Moser, E., Deecke, L., & Beisteiner, R. (2001). Cross-modal plasticity in congenitally blind subjects. *Proceedings of the International Society for Magnetic Resonance in Medicine, 9,* 670. Retrieved April 5, 2007, from http://cds.ismrn.org/ismrm-2001/PDF3/0670.pdf

Lessard, N., Paré, M., Lepore, F., & Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature*, *395,* 278–280.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology: General, 122,* 73–91.

Marchant, B., & Malloy, T. (1984). Auditory, tactile and visual imagery in PA learning by congenitally blind, deaf, and normal adults. *Journal of Mental Imagery*, *8,* 19–32.

Millar, S., & Al-Attar, Z. (2005). What aspects of vision facilitate haptic processing? *Brain and Cognition*, *59,* 258–268.

Pietrini, P., Furey, M. L., Ricciardi, E., Gobbini, M. I., Wu, W. H. C., Cohen, L., Guazzelli, M., & Haxby, J. V. (2004). Beyond sensory images: Object-based representation in the human ventral pathway. *Proceedings of the National Academy of Sciences USA*, *101,* 5658–5663.

Röder, B., Stock, O., Bien, S., Neville, H., & Rösler, F. (2002). Speech processing activates visual cortex in congenitally blind adults. *European Journal of Neuroscience, 16*, 930–936.

Sadato, N., Pascual-Leone, A., Grafman, J., Deiber, M. P., Ibanez, V., & Hallett, M. (1998). Neural networks for braille reading by the blind. *Brain, 121,* 1213–1229.

Sadato, N., Pascual-Leone, A., Grafman, J., Ibanez, V., Deiber, M.-P., Dold, G., & Hallett, M. (1996). Activation of the primary visual cortex by braille reading in blind subjects. *Nature, 380*, 526–528.

Sadato, N., Okada, T., Honda, M., & Yonekura, Y. (2002). Critical period for cross-modal plasticity in blind humans: A functional MRI study. *Neuroimage*, *16,* 389–400.

Smirnakis, S. M., Brewer, A. A., Schmid, M. C., Tolias, A. S., Schüz, A., Augath, M., Inhoffen, W., Wandell, B. A., & Logothetis, N. K. (2005). Lack of long-term cortical reorganization after macaque retinal lesions. *Nature*, *435,* 300–307.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses.* Cambridge, MA: MIT Press.

Sunness, J. S., Liu, T., & Yantis, S. (2004). Retinotopic mapping of the visual cortex using functional magnetic resonance imaging in a patient with central scotomas from atrophic macular degeneration. *Ophthalmology*, *111*, 1595–1598.

Thinus-Blanc, C., & Gaunet, F. (1997). Representation of space in blind persons: Vision as a spatial sense? *Psychological Bulletin, 121,* 20–42.

Tinti, C., Adenzato, M., Tamietto, M., & Cornoldi, C. (2006). Visual experience is not necessary for efficient survey spatial cognition: Evidence from blindness. *Quarterly Journal of Experimental Psychology, 59,* 1306–1328.

Trauzettel-Klosinski, S. (2002). Reading disorders due to visual field defects: A neuro-ophthalmological view. *Neuro-Ophthalmology*, *27,* 79–90.

Ungar, S. (2000). Cognitive mapping without visual experience. In R. Kitchin & S. Freundschuh (Eds.), *Cognitive mapping: Past, present and future* (pp. 221–248). London: Routledge.

Vanlierde, A., & Wanet-Defalque, M. C. (2004). Abilities and strategies of blind and sighted subjects in visuo-spatial imagery. *Acta Psychologica, 116,* 205–222.

Vanlierde, A., & Wanet-Defalque, M. C. (2005). The role of visual experience in mental imagery. *Journal of Visual Impairment & Blindness, 99,* 165–178.

Vecchi, T. (1998). Visuo-spatial limitations in congenitally totally blind people. *Memory*, *6,* 91–102.

Vecchi, T., Cattaneo, Z., Monegato, M., Pece, A., Cornoldi, C., & Pietrini, P. (2006). Why Cyclops could not compete with Ulysses: Monocular vision and mental images. *NeuroReport*, *17,* 723–736.

Vecchi, T., Monticelli, M. L., & Cornoldi, C. (1995). Visuo-spatial working memory: Structures and variables affecting a capacity measure. *Neuropsychologia*, *33,* 1549–1564.

Vecchi, T., Tinti, C., & Cornoldi, C. (2004). Spatial memory and integration processes in congenital blindness. *NeuroReport*, *15,* 2787–2790.

Wolffe, M. (1995). Role of peripheral vision in terms of critical perception—Its relevance to the visually impaired. *Ophthalmic and Physiological Optics, 15,* 471–474.

World Health Organization. (2001). *International classification of functioning, disability, and health.* Geneva: Author.

Zuidhoek, S., Kappers, A. M. L., Noordzij, M. L., Van der Lubbe, R. H. J., & Postma, A. (2004). Frames of reference in a haptic parallelity task: Temporal dynamics and the possible role of vision. In S. Ballesteros & M. A. Heller (Eds.), *Touch, blindness and neuroscience* (pp. 155–164). Madrid: UNED Press.

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