EDUCATIONAL AND REHABILITATIVE INTERVENTIONS FOR EGOCENTRIC AND ALLOCENTRIC FRAMES OF SPATIAL COGNITION IN CONGENITAL BLINDNESS: A MULTIDISCIPLINARY OVERVIEW

INTERVENTI EDUCATIVI E RIABILITATIVI PER I FRAME EGOCENTRICI E ALLOCENTRICI DELLA COGNIZIONE SPAZIALE NELLA CECITÀ CONGENITA: UNA PANORAMICA MULTIDISCIPLINARE

Amalia Maria Paoletta
University of Molise
amalia.paoletta@unifg.it

Leila Ali
University of Pegaso, Nalpes, Italy. University of Camerino, MC, Italy
leila.ali@unicam.it

Luca Refrigeri
University of Molise
luca.refrigeri@unimol.it

Francesca Baralla
University of Molise
francesca.baralla@unimol.it

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ABSTRACT

Navigation depends on spatial cognition (SC). The blind use alternative sensory modalities. This narrartive overview examines SC in the blind, focusing on egocentric and allocentric frames. Showing that unlike egocentric, allocentric orientation is delayed, troubling navigating large-scale environments. Visual cortex's plasticity allows compensatory use of auditory and tactile inputs, partially supporting allocentric abilities. Tailored educational and rehabilitative multisensory interventions can bridge developmental gaps of SC.

La navigazione dipende dalla cognizione spaziale (CS). I non vedenti usano modalità sensoriali alternative. Questa overview esamina la SC e i frame egocentrici e allocentrici nella cecità. Mostra che l'orientamento egocentrico é piu lento dell'allocentrico, creando difficoltà nella navigazione in ambienti grandi. La plasticità della corteccia visiva compensa gli input uditivi e tattili, supportando parzialmente le abilità allocentriche. Interventi educativi e riabilitativi multisensoriali su misura possono colmare i gap nello sviluppo della SC.

KEYWORDS

Multisensory compensation, congenital blindness, allocentric orientation, egocentric orientation, spatial cognition
Compensazione multisensoriale, cecità congenita, orientamento allocentrico, orientamento egocentrico, cognizione spaziale

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Introduction

Spatial orientation is fundamental for navigation in the environment (Gifford et al., 2022). Particularly in congenital blindness, the absence of visual input requires the reliance on alternative sensory modalities, such as auditory, tactile, and proprioceptive cues, to develop spatial knowledge and navigate effectively (Setti et al., 2022). In blindness, orientation is a dynamic and active function that allows the child to interact and connect with the external world through internal, mental, and physical bodily processes (Battistin et al., 2023). Hearing and touch constitute primarily sensory substitutes for spatial navigation, allowing blind children to construct a coherent representation of space and increase their independence through motivation and confidence (Bleau et al., 2022). From the beginning, the child is engaged physically, cognitively, and emotionally (Bleau et al., 2022). This complexity of the relationship between the self and the environment shapes egocentric frames that rely primarily on audition and touch and, to a lesser degree, allocentric frames that seem to rely on more complex processing (Bleau et al., 2022). This phenomenon requires a more precise understanding to help blind children develop spatial autonomy at an early stage of their development. This study will examine the psychological and mental mechanisms of spatial cognition in blind people, focusing on egocentric and allocentric reference frames. It will suggest best practices, innovative technological educational training, and rehabilitative solutions.

1. Theoretical and psychological background of spatial cognition in blind individuals

The specific aspects of spatial cognition compromised by blindness are orientation, mental representation of space, and mental rotation.

1.1. Orientation: Spatial reference frames and Spatial navigation frames.

Spatial reference frames are systems that allow the mental representation of the position of an object from different points of view in space. Within these frames, spatial information can be encoded through categorical spatial relations (e.g., left/right) or coordinate ties (e.g., metric distance) (Ruotolo et al., 2011). Reference frames can be egocentric or allocentric (Ruotolo et al., 2011). In blind people, there is a tendency to associate them with egocentric frames (Pasqualotto et al., 2013), especially on large scales (Iachini et al., 2014). Blindness and severe visual impairment in children lead to developmental delay of allocentric frames (Morelli et al., 2023). Allocentric spatial cognition is defined as the capacity to perceive and comprehend, independent of one's own position or perspective, the spatial relationships between objects and the environment (Ruggiero et al., 2018). Blind children who lack visual input tend to develop their allocentric spatial cognition through other sensory modalities, such as touch and audition (Martolini et al., 2021).

Allocentric spatial coding relies on visual experience in healthy individuals from the first year of life, unlike blind children who remain limited to egocentric frames till adolescence (Martolini et al., 2021). The mechanism of switching from egocentric to allocentric frames and how visual deprivation affects this ability isn't yet well understood (Martolini et al., 2020). Ruggiero et al. conducted a study on congenitally blind individuals to find that allocentric deficit affects the maintenance and combination of different spatial representations that alter the allo-to-egocentric reference frames switching (Ruggiero et al., 2018). In visual feedback, allocentric cues are used preferentially, whereas haptic feedback is more associated with egocentric frames (Kappers & Koenderink, 1999; Martolini et al., 2021; Pasqualotto et al., 2013).

Spatial navigation frames in children develop through early-reaching behaviors. Reaching abilities develop from using egocentric to allocentric reference frames in sighted infants around 6 to 12 months of age and become increasingly allocentric during toddlerhood (Lew et al., 2000). Spatial navigation frames are cognitive systems that allow the planification, guidance, and update of position during navigation in space (Epstein et al., 2017). Montello distinguished in spatial decision-making between locomotion and wayfinding components (Montello, 2005). Wayfinding relies on at least two environmental features, one observer, and the spatial relations between them in its use of egocentric and allocentric reference frames (Shelton & McNamara, 2001). Allocentric frames include geometrical and structural environmental (Shelton & McNamara, 2001), intrinsic orientational (Mou, 2002), and absolute fixed universal directions (Levinson, 1996). They differ from egocentric reference frames by relying primarily on an abstract coordinate system like mental maps (amodal spatial representations) and/or object-to-object relations (Klatzky, 1998). Unlike sighted children, blind infants' reaching abilities are altered in timing, strategy, and precision: While sighted children develop it from 5 months of age, it is delayed till 10 months old in the blind (Cappagli & Gori, 2020). The use of substitute compensatory spatial strategies in blind people can also be delayed (like discrimination of haptic orientation and auditory localization) and associated with less precision than visual cues (Cappagli & Gori, 2020).

1.2. Mental representation of the space: Cognitive Maps, Spatial Memory and spatial reasoning

Cognitive maps are amodal mental representations of the spatial environment that allow a person to remember and strategically navigate spatial cues (Epstein et al., 2017). Sensorimotor coupling and cognitive spatial processes are necessary for allocentric spatial performance, spatial inference (deducting or predicting spatial relationships), spatial updating (tracking and adjusting positions in space during movement), and developing accurate survey knowledge that allows the formation of mental global maps of the environment (Montello, 2005). Amodal spatial representations lack consensus regarding how they shape locomotion and wayfinding because of limitations in methodologies, blindness heterogeneities, and ambiguity in terminologies defining mental maps (Schinazi et al., 2016). Visual impairment could alter the formation and structure of cognitive maps through alterations in spatial learning and wayfinding (Portugali, 1996), and tends to rely more on egocentric spatial tasks in small-scale "local" environments (Martolini et al., 2020) unlike large-scale spaces that require further allocentric perceptual skills (Giudice et al., 2020).

Spatial memory allows us to remember the location and arrangement of objects in space (Setti et al., 2022), while spatial reasoning is the ability to manipulate and understand spatial relationships (Gifford et al., 2022). In the blind, brain plasticity allows relative preservation of spatial memory functioning by enhancing nonvisual sensory processing and the creation of alternative nonvisual cognitive maps (Setti et al., 2022). The generation and manipulation of mental images can occur through long-term memory, haptic exploration, or auditory cues such as verbal description (Carreiras & Codina, 1992; Lederman & Klatzky, 1990; Zimler & Keenan, 1983). Tactile perception in blind people allows the creation of mental images of objects by conveying substitutes for visual features like dimension, shape, and texture (Setti et al., 2022). Spatial reasoning in blind people is adaptable and relies on nonvisual cues. Some challenges and limitations can be observed in mental imagery processing since it depends on auditory and tactile cues, and using egocentric reference frames rather than allocentric ones may limit the analysis of environmental spatial cues (Knauff & May 2006).

1.3. Mental rotation: Mental visualization and rotational transformation

Mental rotation is a key faculty of spatial reasoning that allows people to visualize a mental image of an object and manipulate it by mentally rotating it in one or more axes (Rovira et al., 2011). In blind individuals, mental rotation is still possible. Yet, it is different from the sighted in many aspects (Tivadar et al., 2023): 1- Visualization relies instead on haptic and auditory cues, 2- There is a primary use of egocentric frames of reference or by turning around the object or by rotating it using the hands, and 3- The mental rotation is slower and more sequential. These cited aspects can lead to more difficulties of mental rotation when the number of items increases (Cattaneo et al., 2008; Setti et al., 2022; Vecchi, 1998).

2- Neuroscientific and neurodevelopmental principles of visual imagery, and spatial orientation

2.1. Vision and visual imagery two distinct neurofunctional processes

Vision is a dominant sense in spatial navigation compared to other senses (Gori et al., 2017). The loss of vision in people with blindness can lead to compensatory mechanisms allowing a switch of function of the visual cortex by auditory and somatosensory systems of congenital blindness (Gori et al., 2017). This neuroplastic transformation can compensate for spatial allocentric navigation deficits (Gori et al., 2017). Vision and visual imagery seem to be two distinct functions with different neurofunctional properties: while vision depends mainly on visual circuits and the occipital cortex to perceive external environmental cues, visual imagery is a cognitive imaginative process linked to activation within the attention and cognitive control frontoparietal areas, introspective cognition and memory areas within the default mode network, and visual cortical regions (Fulford et al., 2018). Visualization vividness was also found to be related to activity within the posterior cingulate, fusiform gyrus, and parahippocampal gyri (Fulford et al., 2018). Visualization seems to be preserved to a certain extent, even in congenital blindness. It relies on verbal/semantic, haptic, or purely spatial nonvisual representations and can impact spatial cognition (Cattaneo et al., 2008). Recent studies have even reported that even the congenitally blind can have visual imagery (Kang et al., 2023). This phenomenon is considered associated with genetically predetermined properties of the visual cortex in modulating multisensory representations to create visual-like neural and cognitive representations and create visuospatial images within higher order multisensory integration areas like extrastriate body area, the lateral occipital tactile, visual area, and the fusiform and inferior temporal gyri (Kang et al., 2023). This constatation goes in line with other research on the absence of visualization, also known as blind imagination or aphantasia, that was found to be associated with hyperactivation of the right anterior cingulate cortex and hypoactivation of the fusiform gyri and temporo-occipital regions: outlining the role of the fusiform gyri and temporo-occipital areas of visualization and frontal activity in imagery inhibition (Fulford et al., 2018). This association also shows different neurofunctional dynamics between congenital blindness as a visual sensory deprivation phenomenon and aphantasia as a cognitive dysfunction.

2.2 Neurodevelopmental and neurofunctional aspects of spatial orientation in blind and sighted children

While egocentric orientation relies more on body and limb lateralization, allocentric relies more on posture (Tamè et al., 2019).

- *Egocentric orientation and hand horizontal lateralization:*

Limb and hand lateralization rely mainly on haptic and sensorimotor contingencies (Tamè et al., 2019) and have been shown to develop from 18 weeks of gestational age to become evident at 6 months of age in sighted children (Tomasi & Volkow, 2024). They are controlled by the somatosensory cortex I, which, through interhemispheric communication through the corpus callosum, sends information to associative cortices: the somatosensory cortex II and parietal cortex (Tamè et al., 2019). This function seems well preserved in blind children since visual cues are not mandatory for processing (Ittyerah et al., 2007). Figure 1 summarises the neurofunctional circuitries of egocentric orientation.

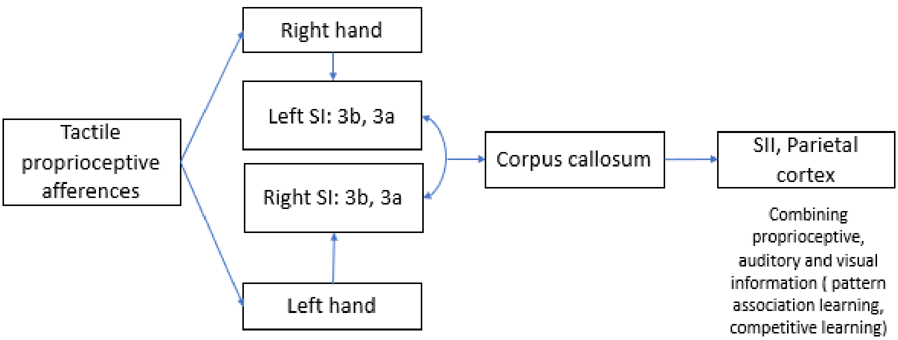


Figure 1. Neurofunctional circuitries of egocentric orientation

- *Allocentric orientation and posture:*

Allocentric orientation develops between the six and 10th months of age in children. It requires both proprioceptive and visual cues that are controlled by higher hierarchy associative areas in the parietal cortex (Area 7b PF) (Rolls, 2023). This function is affected in blind children since it requires principally visual information for processing (Tamè et al., 2019). There are also gender differences in allocentric orientation, with a better-reported performance in males than their female counterparts (Ittyerah et al., 2007). Two types of behavioural functions can be developed in allocentric posture orientation : The spatial priors and the proprioceptive canonical postures (Tamè et al., 2019): 1- Spatial priors are a reference point to localize tactile events (Tamè et al., 2019) and can be visual or proprioceptive (Tamè et al., 2019). They facilitate tactile remapping and configuration (Tamè et al., 2019). Their function is controlled by multimodal neurons with intermediate receptive fields located in the posterior parietal cortex, and their activity is modulated by eyes, hands, and head positions (Tamè et al., 2019). Proprioceptive priors depend on area BA5/PE in the superior parietal lobule, which interferes with complex body postures and joint perception and interpretation of tactile information (Tamè et al., 2019). 2- Proprioceptive canonical postures differ from spatial priors because they require already stored proprioceptive representations (Tamè et al., 2019). This function relies on visuo-tactile attention paradigms to allow storage of representations of the prototypical layout of the limbs (Tamè et al., 2019). Figure 2 summarises the neurofunctional circuitries of allocentric orientation.

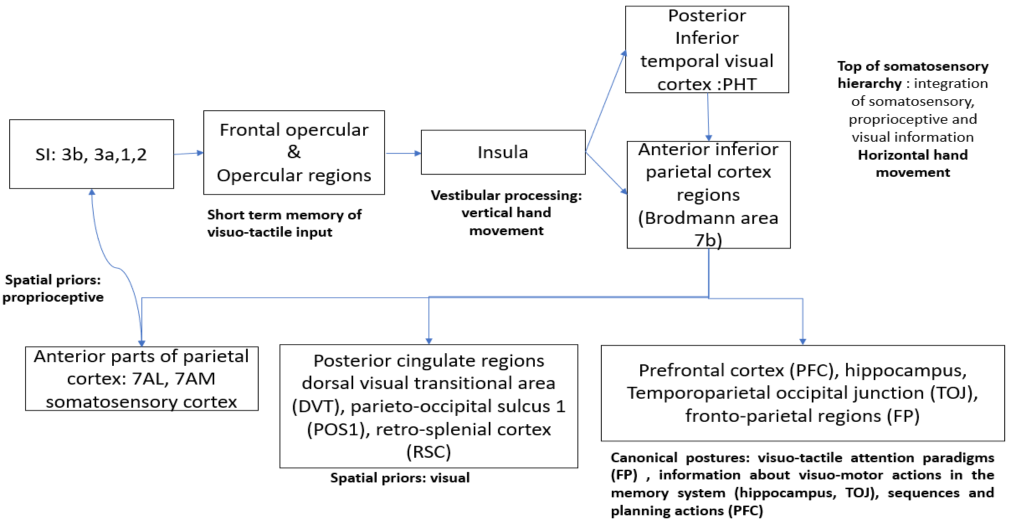


Figure 2. Neurofunctional circuitries of allocentric orientation.

3. Best practices and digital technologies on teaching spatial orientation to blind children

3.1. Theoretical approaches and strategies

One of the primary strategies used in teaching spatial concepts to blind children is multisensory learning (Morelli et al., 2020). This approach engages multiple senses—such as touch, hearing, and proprioception—to convey spatial information (Bakir et al., 2022). Early childhood (ages 3–6) is a critical period for spatial learning, yet blind children face unique challenges in constructing mental representations of their environment without visual input (Cappagli & Gori, 2020). Educators must adopt intentional, multisensory teaching strategies that leverage auditory, tactile, and movement-based learning to foster spatial understanding (Cappagli & Gori, 2020). There are two complementary forms of orientation: static and dynamic. While static orientation focuses on spatial awareness in the absence of physical movement, such as identifying the position of a window in a room through auditory cues or tactile perception of air movement, dynamic orientation depends on movement—walking, reaching, and navigating (Lawrence et al., 1957). These two modes, despite their difference, are complementary processes; children should be encouraged to explore them both directly and reflect on the gathered spatial information. Before children can navigate complex spaces, they must grasp topological concepts—basic relational ideas such as proximity, enclosure, separation, and continuity (Newcombe et al., 2013). These form the scaffolding for later Euclidean (metric) understanding and promote the shift from egocentric to allocentric reference frames. Topological concepts should be taught both on the body and on the plane through external objects. When a child hears a sound coming from the right, the teacher should immediately label it: "That's the bell on your right". The principles of auditory spatial training shouldn't be confined to structured lessons. Educators can reinforce these skills naturally by narrating environmental sounds during playtime ("*Listen—the birds are above us in the trees*"), or playing "sound scavenger hunts" ("*Find the beeping toy near the couch*"), moreover encouraging children to describe where sounds are coming from ("*Is the microwave beeping in front or behind you?*"). The key is to make these activities engaging, repetitive, and language-rich, ensuring that auditory cues become as intuitive and informative as visual ones are for sighted children. Once learned, the focus should shift to movement, navigation, and orientation (Cappagli, 2017).

An important part of spatial learning in blind people involves refining auditory skills (Setti et al., 2018). Audition can be enhanced early to compensate for spatial perception's development because of its capacity to provide information from a distance unlike touch (Setti et al., 2018). Multisensory action-perception training has been proven to improve spatial navigation in visual impairment and even prevent delays in children's development and the social exclusion that can result from that (Cappagli & Gori, 2020). The child learns first to detect obstacles, then to discriminate between different kinds of obstacles, and eventually to perceive the shape of objects through sound. This behavior requires patience, attention, and a gradual sharpening of perception. The ability to hear a room's layout or the garden's structure, for instance, opens up a practical understanding and a deeper appreciation of one's environment. The training should focus on interpreting subtle auditory cues—such as slight delays in sound arrival between ears (binaural timing differences) or variations in pitch and volume—to determine where objects are in space. The educational implication is profound: if we can train blind children to attend to these cues consciously, we can accelerate their spatial cognition. While auditory input provides distal information, tactile and movement-based experiences ground spatial understanding in the body.

3.2 Educational technologies for spatial orientation training for blind children

- Blind Interaction Audio Bracelet (Figure 3a):

Ben Porquis et al. (2017), developed a wearable device ABBI (Audio Bracelet for Blind Interaction), designed to enhance spatial perception in Children with visual impairment through multisensory rehabilitation training especially auditory feedback triggered by movement. The study demonstrated that congenitally blind children significantly improved spatial tasks after using ABBI. In contrast, low-vision children did not benefit as much, likely due to residual visual input already supporting their spatial development (Ben Porquis et al., 2017).

- Tactile maps: MapSense (figure 3b)

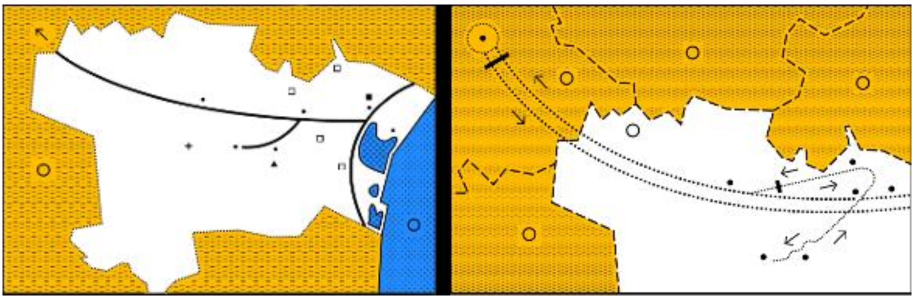
Tactile maps allow children to explore space layouts through raised-line representations, creating a mental anchor for real-world navigation. Children can comprehend the design of spaces and objects through a tangible representation of their surroundings. Multisensory technological enhancement of classic tactile maps using tangible 3D surfaces was used in MapSense to support geography learning for children with visual impairment (Brule et al., 2016).

- Multisensory interventions: AudioDoom (Figure 3c) and LOI (Figure 3d)

AudioDomm uses tangible combined to interact with a 3D audio hyperstory to embed in a narrative context through active participation, spatial concepts such as spatial awareness and orientation in blind children, as well as other cognitive functions such as decision-making and problem-solving (Sánchez & Lumbreras,

1999). The tactile component of this intervention happens through LEGO construction that is combined with different auditory stimuli, helping children create multisensory mental maps (Sánchez & Lumbreras, 1999)
LoI (*Legend of Iris) by* Allain et al targeted older blind children between 16 and 19 years of age, and used a combination of puzzles, and 3D audio sound localized through head tracking to train spatial navigation (Allain et al., 2015).
Cognitive functions stimulated through this serious game were sound localization, filtering distractions, tracking moving objects, and spatial memory (Allain et al., 2015).

3a. 

3b. 

3c. 

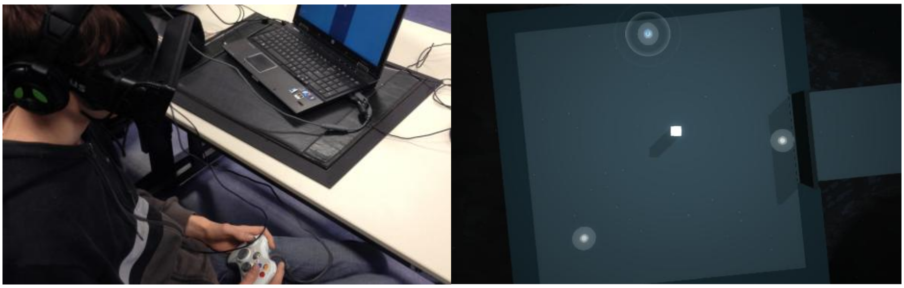
3d. 

Figure 3a. ABBI Bracelet (Ben Porquis et al., 2017); 3b. On the right there is a map of a region in France having points of cultural interests. The map on the left has a class trip itinerary (Brule et al., 2016); 3c. AudioDoom functioning and lego blocks function (Sánchez & Lumbreras, 1999); 3d. Legend of Iris made visual (Allain et al., 2015).

Conclusions and future perspectives

Spatial cognition and spatial orientation can still be functional in congenital blindness despite vision loss due to cross-modal cerebral plasticity that compensates for vision deficit by nonvisual somatosensory and auditory cues. Unlike egocentric orientation, allocentric orientation can be affected in congenital blindness due to its reliance on visual cues for processing. Understanding the neurofunctional and behavioral differences between sighted and congenitally blind children allows the development of tailored educational and rehabilitative interventions to stimulate the affected specific dimensions of spatial cognition in this population and improve allocentric reference frames deficits.

Author contributions

Amalia M. Paoletta wrote section 1., 3.
Leila Ali wrote the Introduction, and section 2.
Prof. Luca Refrigeri and Prof. Francesca Baralla reviewed the sections 1., 3. And wrote conclusions.

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