Chapter

The Role of Vision on Spatial Competence

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Abstract

Several pieces of evidence indicate that visual experience during development is fundamental to acquire long-term spatial capabilities. For instance, reaching abilities tend to emerge at 5 months of age in sighted infants, while only later at 10 months of age in blind infants. Moreover, other spatial skills such as auditory localization and haptic orientation discrimination tend to be delayed or impaired in visually impaired children, with a huge impact on the development of sighted-like perceptual and cognitive asset. Here, we report an overview of studies showing that the lack of vision can interfere with the development of coherent multisensory spatial representations and highlight the contribution of current research in designing new tools to support the acquisition of spatial capabilities during childhood.

Keywords: blindness, visual impairment, child development, rehabilitation, innovation

1. Introduction

Spatial competence is essential in everyday life for numerous human activities, as it entails the ability to understand and internalize the representation of the structure, entities, and relations of space with respect to one's own body [1, 2]. Despite the fact that spatial competence encompasses a diverse set of skills, research in the field has generally focused on identifying the developmental steps that are necessary to acquire from an early age the ability to reason about spatial properties of the environment.

There is a general consensus on the crucial role of visual experience in guiding the maturation of spatial competence [3]. Vision takes advantages respect to other senses in encoding spatial information because it ensures the simultaneous perception of multiple stimuli in the environment despite the apparent motion of the array on the retina during locomotion enabling us to extract more invariant spatial properties from the surrounding layout [4, 5]. Indeed psychophysical data indicate that when sensorial conflict occurs, audition and touch are strongly biased by simultaneously presented visuospatial information, suggesting that sighted people tend to organize spatial information according to a visual frame of reference [6–12]. Neurophysiological data further confirm the view by suggesting that the visual feedback is fundamental for spatial learning [13–18], i.e., visual experience allows the alignment and thus the integration of auditory and visuospatial cortical maps [19–22]. Thus, research on sighted individuals suggests that vision typically provides the most accurate and reliable information about the spatial properties of the external world, therefore it dominates spatial perception. Consequently, if visual experience is necessary to adequately represent spatial information, we would expect blind people to perform worse than sighted people in spatial tasks. This would be especially true if the visual impairment emerges at birth, when multisensory communication is fundamental for the sensorimotor feedback loop that contributes to the development of spatial representations [23, 24].

Despite valuable insights into the important guiding role of vision on spatial development, contrasting results indicate that visually impaired people can manifest or enhanced either impaired skills depending on the spatial aspects investigated, leading to the hypothesis that vision could have an essential or facilitating role depending on the nature of the spatial task that individuals carry out [14]. A clearer definition of the underlying processes involved in spatial competence enhancements and deficits caused by visual loss is important not only to quantify to what extent the perceptual consequences of early blindness translate to real-world settings but also to develop effective rehabilitation tools and technologies to improve their spatial skills [25]. Indeed, scientific findings related to spatial competence development in the absence of visual experience have important implications for clinical outcomes and for the design of new rehabilitation activities meant to activate compensatory strategies since an early age.

2. Development of spatial competence with vision

The first developmental theory of spatial competence was proposed by Jean Piaget and his colleagues [26–28], who hypothesized that spatial understanding gradually improves with age thanks to a progressively more conscious interaction with the external world that permits to accumulate sensorimotor experiences such as reaching. Nonetheless, the identification of the starting points for spatial development remains one of the most debated topics within the literature of spatial competence.

While some researchers argue for innate knowledge of spatial understanding in humans [29] by reporting impressive spatial abilities in infants, other researchers advocate for a gradual acquisition of spatial competence during childhood [30] by reporting significant limitation of early spatial skills during infancy. For instance, several studies have demonstrated that already at 3 months infants are able to represent categorical spatial information by distinguishing between above vs. below and left vs. right [31, 32] and that by 5 months of age babies are sensitive to metric properties of space being able to code spatial object dimensions such as height [33–35], distance location [36], and angles [37]. Conversely, other studies indicate that while sensitivity to spatial properties appears in early infancy, further refinement of spatial accuracy emerges later during development. For instance, coding of categorical and metrical information improves through the primary school years [38–40] as well as capabilities of estimating and reproducing object size and location [41, 42].

The question of whether spatial capabilities are innate or acquired is of central importance to understand if an early sensory deprivation can negatively impact on the acquisition of adult-like competences. In the case of blindness, a key developmental acquisition is the ability to code auditory and tactile spatial properties of the environment in order to independently orient and navigate in space. Research on auditory spatial perception has shown that sighted infants already possess the ability to differentiate acoustic information and perform adequate actions in different dimensions [43]. Indeed they can turn their heads toward a sound from the moment they are born [44, 45] and at the age of 4–5 months, head-orientation movements become even faster and more precise than in the neonatal period. Further improvements in the ability to code the location of sonorous objects in space manifest at 6 months of age, when infants are sensitive to changes in the location of sounds as small as 13–19 degrees [46, 47]. Nonetheless, this reflexive orientation to sound sources is present at birth but disappears during the first month if large movements of the head are required [48] to appear again at 4–5 months of age: for this reason, it has been hypothesized that the early orientation reflex represents the activity of lower brain stem and provides an initial stage to acquire spatial competence [49] that is later consolidated through concrete experience.

In the spatial cognition domain, two main distinctions can be made about spatial representations of the environment [50]. The first distinction is between the egocentric and allocentric frame of reference which indicates the strategy to code location of objects, respectively, in a viewer-dependent or a viewer-independent manner. While the egocentric representation is tied to the observer and can be used either when the observer remains stationary or when the observer moves keeping track of the movement (dead reckoning or path integration), the allocentric representation does not depend on the viewer's current position but on external landmarks that can be adjacent (cue learning) or distal (place learning). Although early spatial representations were originally described as purely egocentric [51], several studies indicated that infants can make use of both intrinsic and external features of the environment to locate objects. There is evidence that infants can update egocentric representations by keeping track of their movement and thus locate objects from novel positions within the first year of life: indeed by 9 months, infants can compensate for simple changes in their position, such as translation along a straight line [52] or rotational movements [53]. Nonetheless, for more complex displacements, infants manifest a general difficulty in keeping track of their changing relation to target location. For example, at 12 months of age, they start to solve complex problems involving both translation and rotation but they perform better when they can make use of adjacent landmarks embedded in the environment [54], and this ability seems to show little improvement between 16 and 36 months [55]. Moreover, previous research has shown that sighted infants reach for sounding objects in the absence of visual clues [47, 56–59], implying that a sense of auditory space is well consolidated at this stage since sounding objects are localized in relation to one's body. The allocentric strategy seems to emerge quite early in the development together with the egocentric strategy, but with different maturational rates for cue learning and place learning types of coding. Indeed, studies employing paradigms where the direction of looking from a novel position indicate where infants expect to see an engaging stimulus demonstrate that by 8.5 months of age, infants use an adjacent salient landmark to locate the stimulus, whereas only at 12 months of age, they consistently use relational information of distal landmarks [54]. Several studies confirm the idea that egocentric and allocentric strategies continue to refine during childhood by showing that at 18–24 months of age, toddlers become able to use geometrical cues such as shape to orient themselves [60, 61]. Nonetheless, an important milestone such as the ability to integrate different reference frames within a common system of spatial representation in order to increase accuracy and reduce the variability of spatial judgments emerge only later during the development. Indeed, children aged between 4 and 8 years old are not able to use both self-motion and external landmarks as egocentric and allocentric information, respectively, to reproduce object location because they alternated both strategies instead of combining them as adults usually do [62].

The second distinction in the spatial cognition domain is between categorical and metric spatial representations, which, respectively, represent the coding of spatial information in a relative manner by means of comparisons among entities in space and the coding of spatial information in external coordinates by means of metric cues such as distance or length. It has been shown that at 7 months of age, infants spontaneously show categorical dichotomous discrimination of auditory space by differentiating objects within and beyond reach [57, 58] and by distinguishing spatial categories such as above vs. below and left vs. right [32, 63]. Early sensitivity to metric cues has been observed in 4.5–6.5 months old infants for the dimension of objects [64] and distance [36]. Nonetheless, methodological issues have been raised for the interpretation of such results since experimental paradigms typically used with infants employ observational measures of the infant's behavior that may reveal more low-level perceptual rather than conceptual representation. Indeed, it has been shown that at the age of 2 years, children are able to match objects by height when these objects are presented in containers of a fixed height, but not when they are presented without containers, indicating that toddlers make use of distance cues only when they can rely on relative cues [65]. A considerable improvement in the ability to code object size and location can be observed between the ages of 4 and 12 [40–42, 66], for example, in tasks that require to use a configuration of distal landmarks to infer object location [67]. This could be due to the development of a hierarchical coding system, which integrates metrics and categorical information [68]. Given the time course of spatial cognition development and the discrepancy between early and later acquisition of spatial skills, an interactionist approach has been proposed that acknowledges strong potentiality and tries to identify underlying mechanisms implicated in the transformation of early abilities into mature competence [69]. The underlying mechanisms responsible for the refinement of spontaneous spatial orientation skills might be found both in the biological and environmental experiences. Within the biological context, many improvements in spatial functioning have been associated with the maturation of specific brain regions such as the hippocampus. For instance, the maturation of the hippocampus-mediated ability to encode relations among multiple objects may determine an increase in the number of stimuli that children rely on during reorientation and navigation tasks [70]. Within the environmental context, experience involves interactions with objects in the physical world and learning conventional information about symbolic spatial representations, such as maps and models. Spatial competence is strictly dependent on experiential factors such as exploratory activities which are in turn related to the development of locomotor activities. For example, it has been suggested that the emergence of allocentric coding in the form of cue learning might derive from the onset of crawling around 8–9 months, while further locomotor experiences may facilitate place learning by stimulating children to observe and approach object arrays from different directions. Indeed, locomotion is not simply a maturational precursor to psychological changes, but it plays a crucial role in their genesis [71]. For example, crawling provides the infant with concrete experiences that may change his coding strategy, for example, permitting the infant to abandon an egocentric body-oriented localization of objects to one based on the use of environmental landmarks. Recent findings suggest that sighted children acquire spatial capabilities thanks to the reciprocal influence between visual perception and execution of movements [72]: children monitor the success of action through a sensory-motor feedback by matching expected and observed changes of visual information. Indeed, self-generated movements commonly help to perceive the space acoustically because they convey the proprioceptive sensation corresponding to the movement of the ears toward sound sources [73]. In other words, using the dichotomy between the body and its exterior, an individual acquires spatial competence through observation of the body's actions and the resulting sensory consequences: through self-generated movements, the nervous system learns sensorimotor contingencies [74], which reveal the spatial properties of the auditory space. Moreover, acting successfully entails affordances for action: since affordances change according to action capabilities and bodily characteristics, experiential factors are necessary especially during infancy when new skills are constantly appearing and bodily dimensions are changing rapidly [75].

These results suggest that early interaction between the visual input and other sensory and motor signals provides a powerful background to shape the development of spatial cognition in sighted children. But if vision is so important, how spatial development changes when the visual input is missing?

3. Development of spatial competence in the absence of vision

While the development of spatial cognition has been extensively studied in sighted individuals [50], less effort has been spent in understanding how the sense of space changes during development in children with visual impairment. Specifically, scientific research on the development of auditory localization skills in visually impaired children has provided contrasting results. For example, it has been shown that children with visual disabilities have an excellent spatial hearing, measured as the ability to discriminate differences in sound localization in the horizontal and vertical plane as well as the ability to reach or walk toward the sound source position [76]. On the contrary, several studies suggested that infants and children with severe congenital blindness have a developmental delay in sound localization abilities [23, 77–79] and motor responses to sound [80, 81]. For example, blind children do not reach for objects that produced sounds until the end of the first year, while sighted children start around 5 months [82]. Similarly, blind children show worse performances than sighted children in auditory bisection, minimum audible angle tasks [23], and audio depth tasks [78]. Other studies show mixed results, indicating that children with congenital visual disabilities show an initial neuromotor developmental delay but compensate for the lack of vision developing good manipulatory and walking skills thanks to the exploration of sounding objects in the environment [83]. Studies of proprioceptive localization of immediate and memorized targets have been used to compare the proprioceptive performance of sighted and blind individuals. For instance, it has been shown that early visual deprivation does not necessarily prevent the development of spatial representations in both early blind children [84] and adults [85]. Considering that spatial competence emerges gradually thanks to the reciprocal influence between visual perception and execution of movements [72], it is evident that visually impaired children not only lack the visual input necessary to establish the sensorimotor feedback that typically promotes spatial development, but also manifests a general delay in the acquisition of important locomotor and proprioceptive skills, which may cause them to accumulate much less spatial experience compared to their sighted peers [79, 86, 87]. It has long been known that the development of blind infants is delayed in self-initiated postures and locomotion [79, 88, 89]. While sighted children typically start to perform first individual actions and navigation from the first year of age, blind children without cognitive and motor impairments start to walk at about 30–32 months of age [90]. Moreover, from the first month of life, blind infants show delays in the vestibular and proprioceptive functions due to the lack of integration with the visual inputs typically provided during the development [91]. Finally, since visual feedback represents the most important incentive for actions and thus for the development of locomotion and mobility skills, the onset of several motor milestones (e.g., rolling, crawling, standing, and balancing) can be delayed in visually impaired infants [92, 93], suggesting that the visual feedback of the body is fundamental for the development of self-concept.

To perceive space, visually impaired children typically use hearing and touch. Despite the haptic sense provides essential information about the spatial layout of peripersonal space, such as the size, shape, position, and orientation of objects within reach, it typically conveys information only within the scope of the body. The case of hearing is particularly interesting because the auditory sense is not only the main channel for providing distal information but also it might be superior to all other sensory alternatives because it provides spatial information in both active and passive conditions and it does not necessarily involve direct contact with objects [94, 95]. At the same time, the use of hearing to perceive distal information might be particularly difficult for visually impaired children because in this case, they do not have any sensory feedback about sonorous objects in the far space. On the contrary, the haptic-proprioceptive system can provide accurate spatial data only within the scope of the body itself [96], and therefore a blind person must actively move in the environment to sequentially touch all the stimuli embedded in space. Several factors may contribute to increasing the difficulty in interpreting such contrasting results. For example, many studies on spatial hearing have been conducted within the framework of broader research on cognitive and motor skills development [87, 97] and reaching mixing the motor and the perceptual component of the observed behavior [83, 98]. In addition, different methodological approaches and stimuli have been used to assess similar aspects of auditory spatial perception: for instance, studies performed on visually impaired children under 3 years of age do not employ psychophysical procedures but they frequently use the sound of familiar voices or toys to gather information about auditory localization abilities in blind children [97]. In addition, in some cases, sighted and blind groups of children are not perfectly matched for age range and sometimes use also adults as comparison [76]. Finally, the difference between early and later loss of vision has not been often considered: many studies mix data from children with no visual experience with those of children with partial visual experience in the first period of life [76]. Instead, it has been demonstrated that the onset of blindness has a strong impact on spatial performance in adulthood: for example, late blind individuals who lost vision later in life after a normal visual experience during the first year of life perform equally or even better than sighted participants in several auditory spatial tasks (1, 50, 83, and 300). To summarize, although compensatory mechanisms for spatial perception have been demonstrated in blind adults, it is not clear whether an early visual impairment might delay the development of special auditory spatial skills. The development of spatial cognition is strictly related to the development of social cognition: the ability to independently navigate and orient ourselves in space facilitates engagement in social interactions. Indeed, a delay in the acquisition of language, motor or cognitive skills can have a direct impact on a child's social competence (106, 109, and 246). More recent works highlighted that preschool-age children with visual impairments often have difficulties engaging in positive social interactions, making their assimilation into preschool programs difficult. In fact, many do not display a full range of play behaviors [99–103] and spend more time engaging in solitary play interacting more with adults than with their sighted peers [81, 87, 89, 102–107]. Considering that the interaction among peers is essential for the development of cognitive, linguistic, social, and playing skills [108], the aforementioned delay in the acquisition of social competence in visually impaired children gives rise to feelings of frustration, rather than self-efficacy and independence which characterize the social experience of typical children. Indeed, the lack of visual information during early infancy often constitutes a risk for the development of the personality and emotional competence [89]. Nonetheless, when assessing social competence in visually impaired people, some other factors resulting from the loss of vision should be taken into account. For example, it has been shown that parenting style influences the socio-emotional development of

DOI: http://dx.doi.org/10.5772/intechopen.89273

sighted children [109–113] because parents represent the first influential setting that can produce appreciable differences in developmental outcomes in terms of psychological functions [114, 115]. Inconsistent, hostile and nonsensitive parenting behaviors have been associated with adjustment problems and social adversity during childhood [116, 117] and also with anxiety, depression, and other stress-related illnesses during adolescence [118, 119] and adulthood [120]. We speculate that a similar influence of parenting style holds also for blind children, especially because families of children with visual disabilities are more prone to experience various stressors such as concerns about the social acceptance of the child [121] and to face difficulties in initiating and sustaining social interactions [122], thus they might easily develop an overprotective behavior that negatively influences the social development of the visually impaired child. The negative effects of blindness on socio-emotional competence can be observed also in adulthood, with the impoverishment of the ability to perform everyday activities both in private settings like home and in public settings like workplace. Importantly, the decrease of functional abilities has been linked to the emergence of serious psychological problems in the blind population [123]. Indeed adults with visual impairments tend to feel more socially isolated and not properly supported compared to sighted individuals [123–126] and are at higher risk of developing depressive symptoms [105, 125, 127–131], principally because social competence depends on the ability to utilize visual cues [132]. Overall, several scientific findings suggest that visual impairments, especially if acquired later in life, can have profound consequences for the physical functioning, psychological well-being, and health service needs of older adults [133]. Consequently, early therapeutic interventions specifically focused on activities fostering the development of perceptual and motor abilities would improve the quality of life of children and adults with visual impairments. In the next section, we will present some tools developed to improve perceptual skills of visually impaired individuals and propose a new solution we recently developed for early intervention in visually impaired children.

4. Spatial tools for visually impaired children

The acquisition of spatial competence is typically a good indicator of the future ability to independently navigate in the environment and engage in positive social interaction with peers. While for sighted individuals, the visual feedback represents the most important incentive for actions and thus for the development of mobility and social skills, visually impaired individuals strongly rely on auditory and tactile landmarks to encode spatial and social information. Thus, the creation of technological devices to support visually impaired children in their spatial and social development would be a need. Nonetheless, despite the huge recent advancements in technological industry, most of the devices developed so far to address visually impaired population's needs are not widely accepted by adults and not easily adaptable to children [134].

As reported in the previous sections, visual impairments can determine spatial and social impairments during development. Technological support for the blind should fulfill two different but complementary tasks: the first is to substitute the absent sensory information (vision) with other sensory signals (audition and touch) for daily activities, and the second is to support the rehabilitation of impaired functions following sensory loss. This latter aspect is particularly important when the visual impairment occurs during the first year of life, because technological devices might represent an opportunity for children to develop perceptual and cognitive abilities by compensating for the sensory deprivation. Most of the technological supports developed to date have fulfilled mainly the first task, namely the substitution of vision with other modalities for everyday tasks such as object recognition.

Sensory substitution devices (SSDs) convert the stimuli, normally accessed through one sensory modality, into stimuli accessible to another sensory modality. Specifically, sensory substitution devices for visually impaired individuals aim at supplying the missing visual information with visual-to-tactile or visual-to-auditory conversion systems [135]. Typically, substitution systems based on visual-to-tactile conversion transforms images captured by a camera into tactile stimulations directed to users. From the first device developed in the mid-1960s by Bach-y-Rita (Tactile-Visual Sensory Substitution device or TVSS), that converts signals from a video camera into tactile stimulation applied to the back of the subject allowing for the recognition of lines and shapes [136], recent technological progress allowed the development of much smaller, portable, and wearable devices. For instance, wristbands, vests, belts, and shoes which allow hands-free interactions [137] and devices that can be placed on various body surfaces (e.g., fingers, wrist, head, abdomen, and feet) [138, 139]. Conversely, systems based on visual-to-auditory conversion transform the images captured by a camera into sounds transmitted to users via headphones. One of the most famous visual-to-auditory devices is the vOICe developed by Meijer [140] that associates height with pitch and brightness with loudness in a left-to-right scan of the visual image.

In our recent review, we listed the SSDs designed for visually impaired individuals by highlighting their main features and limitations for daily use [134]. In particular, we identified six main limitations that might determine low acceptance rate in adults and low adaptability in children:

- Invasiveness: SSDs can be physically invasive in the sense that in order to be used, they must be positioned on crucial body parts (e.g., ears or mouth), thus limiting perceptual functions in users or they must be transported (e.g., in backpacks), thus limiting users' navigation for weight and size;

- Extensive training: SSDs typically require long periods of training in order to be used because users need to learn how to interpret the output of the device, which is typically not immediate (e.g., sound loudness corresponds to pixel brightness in the vOICe [141]);

- High cognitive load: SSDs usually require high attentional resources, which makes it difficult for the user to focus on the main task they are performing when using the device;

- No clinical validation: SSDs frequently remain prototypes and do not reach the blind users market, principally because they are not validated on large sample patients through standardized clinical trials;

- Artificiality: SSDs are generally based on the idea that users can understand the properties of visual stimulus by listening (in the case of visual-to-auditory SSDs) or feeling (in the case of visual-to-tactile SSDs) a stimulus resulting from an artificial transformation code, missing an important aspect of the learning process, which is the association of action and perception.

Therefore, while sensory substitution devices have been shown to provide support for specific perceptual tasks in adults [142], they have never been tested in children principally because their use might too overwhelming for children. Nonetheless, technological development should be addressed especially to visually impaired children needs because cortical plasticity is maximal during the first year of life, therefore the benefit deriving from early interventions should be higher.

Moreover, technological development should lead to multimodal stimulation whose benefits have been repeatedly reported compared to unimodal stimulation [143–145], while most of the SSDs developed so far substitute the visual function with either the auditory or the tactile modality alone.

With this in mind, we developed a new device for visually impaired children (Audio Bracelet for Blind Interaction, ABBI, [146]), which is an audio bracelet that produces an auditory feedback of body movements when positioned on a main effector such as the wrist in order to provide a sensorimotor signal similar to that used by sighted children to construct a sense of space. Indeed, several reports indicate that sighted children typically acquire spatial competence by experiencing visuomotor correspondences [72]. In this sense, our device could be used to align the spatial understanding between one's own body and the external space through coupling auditory feedback with intentional motor actions. The audio movement created by the bracelet conveys spatial information and allows the blind user to build a representation of the movement in space in an intuitive and direct manner.

We validated the ABBI device with a clinical trial on an Italian sample of 44 visually impaired children aged 6–17 years old assigned to an experimental (ABBI training) or a control (classical training) rehabilitation condition. The experimental training group followed an intensive but entertaining rehabilitation for 12 weeks during which children performed ad-hoc developed audio-spatial exercises with the Audio Bracelet for Blind Interaction (ABBI). The clinical trial consisted of three sessions: pre-evaluation, training, and post-evaluation. Pre- and post-evaluation sessions lasted 60 min during which a battery of spatial and motor tests were performed [147]. The BSP (Blind Spatial Perception) battery comprised six tests: (1) auditory localization: the child listens to the sound produced by a set of loudspeakers positioned horizontally in front of him/her and localizes the sound source by pointing to it with a white cane; (2) auditory bisection: the child listens to a sequence of three sounds presented successively by a set of loudspeakers positioned horizontally in front of him/her and verbally reports whether the second sound is closer in space to the first or to the third one presented; (3) auditory distance: the child listens to two consecutive sounds produced by a set of loudspeakers positioned vertically in front of him/her in depth and verbally reports which of the two stimuli presented is closer in space to his/her own body; (4) auditory reaching: the child listens to a static sound positioned in far space and reaches the position of the sound by walking toward it; (5) proprioceptive reaching: the child repeats a movement trajectory after being presented with it by an external operator; (6) general mobility: the child walks straight on for three meters and then back to the starting position at his/her own pace. The training session lasted 12 weeks and children were assigned to the experimental training condition based on activities with the use of ABBI or to the classical training condition based on psychomotor lessons not necessarily involving sound localization activities. All children enrolled in the ABBI training group performed weekly training exercises with a trained rehabilitator for 45 min (9 h over 12 weeks) and weekly training sessions with a relative at home for 5 h (60 h over 12 weeks) for a total training period of 69 h. All training exercises were developed to train children' ability to recognize and localize sounds in space according to different levels of difficulty: (a) recognize and localize simple sound movements, such as a straight motion flow performed along the horizontal or sagittal planes in the front peri-personal space (first level); (b) recognize and localize complex sound movements, such as a motion flow performed randomly in space in the front peri-personal space, e.g., composite geometrical and nongeometrical figures (second level); (c) recognize and localize simple and complex sound movements in the back peri-personal space (third level); (d) recognize and localize simple and complex sound movements in the front and back in the extra-personal

	ABBI training	Control training	ABBI vs Control (p value)	ABBI Follow-up	ABBI vs ABBI Follow-up (p value)
	ΔA = T1 – T0, N= 18	ΔC = T1 – T0, N= 20	ΔA – ΔC	ΔA2 = T2 – T0, N= 10	ΔA – ΔA2
Auditory localization	2.80 (1.48) **	1.15 (0.78)	0.0001 ***	3.83 (2.22)	0.17
Auditory bisection	2.43 (2.12) ***	0.15 (0.66)	0.0005 **	3.18 (2.83)	0.11
Auditory distance	0.88 (2.41)	0.98 (1.66)	0.62	3.06 (1.93)	0.99
Auditory reaching	25.48 (12.12) ***	3.95 (12.19)	0.0005 **	17.12 (9.89)	0.17
Proprioceptive reaching	16.44 (10.40) ***	9.89 (7.18)	0.01 **	23.78 (17.92)	0.66
General mobility	3.53 (2.59) **	1.94 (0.95)	0.04 *	2.97 (2.78)	0.44

*One year follow-up of the ABBI group (T2-T0). In order to evaluate the effects within groups, two-tailed t-tests assuming equal variances were performed between groups at baseline (T0) and post-training period (T1). Changes in the outcome measures were then calculated between baseline (T0) and post-training period (T1) in the ABBI training and classical training group (ΔA and ΔC), and between baseline (T0) and follow-up period (T2) in the ABBI training group (ΔA2). Data are presented as mean and standard deviation. The stars indicate the statistical significance of the corresponding t-test of the score difference (*p < 0.05; **p < 0.01; ***p < 0.001). Table readapted from [148].*

Table 1.
Score difference (Δ) after 12 weeks training (T1-T0).

space (fourth level). The comparison of overall spatial performance before and after the training with a dedicated assessment battery indicated that the ABBI device is effective in improving spatial skills in an intuitive manner (see **Table 1** for a summary of results), confirming that in the case of blindness perceptual development can be enhanced with naturally associated auditory feedbacks to body movements [148]. Moreover, the validation of the ABBI device demonstrated that the early introduction of a tailored audio-motor training could potentially prevent spatial developmental delays in visually impaired children [149].

5. Conclusions

Visual experience is deemed to be fundamental for the acquisition of spatial competence; indeed, visually impaired children tend to manifest impairments in spatial and locomotor skills, causing a general developmental delay. The hearing sense can be boosted since an early age to foster compensatory mechanisms for the development of spatial perception, principally because compared to touch it can provide distal information [150]. There is evidence that multisensory training based on the action-perception link can improve spatial abilities in visually impaired children and prevent the risk of developmental delays and social exclusion [148, 149, 151].

Acknowledgements

We would like to thank all the children and parents for their willing participation in our studies and the Unit for Visually Impaired People (UVIP) members for their passionate work on visually impaired individuals.

Conflict of interest

The authors declare no conflict of interest.

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