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Spatial representation and visual impairement

Developmental trends and new technological tools

for assessment and rehabilitation

by

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Chiara Martolini
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Abstract

It is well known that perception is mediated by the five sensory modalities (sight, hearing, touch, smell and taste), which allows us to explore the world and build a coherent spatio-temporal representation of the surrounding environment. Typically, our brain collects and integrates coherent information from all the senses to build a reliable spatial representation of the world. In this sense, perception emerges from the individual activity of distinct sensory modalities, operating as separate modules, but rather from multisensory integration processes. The interaction occurs whenever inputs from the senses are coherent in time and space (Eimer, 2004). Therefore, spatial perception emerges from the contribution of unisensory and multisensory information, with a predominant role of visual information for space processing during the first years of life. Despite a growing body of research indicates that visual experience is essential to develop spatial abilities, to date very little is known about the mechanisms underpinning spatial development when the visual input is impoverished (low vision) or missing (blindness).

The thesis's main aim is to increase knowledge about the impact of visual deprivation on spatial development and consolidation and to evaluate the effects of novel technological systems to quantitatively improve perceptual and cognitive spatial abilities in case of visual impairments. Chapter 1 summarizes the main research findings related to the role of vision and multisensory experience on spatial development. Overall, such findings indicate that visual experience facilitates the acquisition of allocentric spatial capabilities, namely perceiving space according to a perspective different from our body. Therefore, it might be stated that the sense of sight allows a more comprehensive representation of spatial information since it is based on environmental landmarks that are independent of body perspective. Chapter 2 presents original studies carried out by me as a Ph.D. student to investigate the developmental mechanisms underpinning spatial development and compare the spatial performance of individuals with affected and typical visual experience, respectively visually impaired and sighted. Overall, these studies suggest that vision facilitates the spatial representation of the environment by

conveying the most reliable spatial reference, i.e., allocentric coordinates. However, when visual feedback is permanently or temporarily absent, as in the case of congenital blindness or blindfolded individuals, respectively, compensatory mechanisms might support the refinement of haptic and auditory spatial coding abilities. The studies presented in this chapter will validate novel experimental paradigms to assess the role of haptic and auditory experience on spatial representation based on external (i.e., allocentric) frames of reference. Chapter 3 describes the validation process of new technological systems based on unisensory and multisensory stimulation, designed to rehabilitate spatial capabilities in case of visual impairment. Overall, the technological validation of new devices will provide the opportunity to develop an interactive platform to rehabilitate spatial impairments following visual deprivation. Finally, Chapter 4 summarizes the findings reported in the previous Chapters, focusing the attention on the consequences of visual impairment on the developmental of unisensory and multisensory spatial experience in visually impaired children and adults compared to sighted peers. It also wants to highlight the potential role of novel experimental tools to validate the use to assess spatial competencies in response to unisensory and multisensory events and train residual sensory modalities under a multisensory rehabilitation.

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Chapter 1

Introduction

The ability to integrate sensory information is fundamental to understand the basic mechanisms of human perception (Alais and Burr, 2004; Ernst and Banks, 2002; Gori et al., 2013, 2012b, 2011; Squeri et al., 2012; Stein, 2012; Barry E. Stein and Meredith, 1993; Tomassini et al., 2011; Trommershauser et al., 2011), and it is based on cross-modal convergence processes (Soto-Faraco et al., 2019) that are not attributable to merely statistical redundancy, i.e. a simple combination of unisensory responses (Colonius and Diederich, 2004; Laurienti et al., 2004; Maddox et al., 2015; Molholm et al., 2002; Murray et al., 2005).

Spatial perception is typically acquired thanks to the reciprocal interaction among visual, auditory, and haptic feedback related to our body and external objects in the environment (Barry E. Stein and Meredith, 1993). Therefore it is considered a multisensory process by nature. Nonetheless, since our perception tends to be dominated by the sensory modality that provides the most accurate and reliable information about the world, spatial perception is generally dominated by vision that provides the most accurate and reliable information about external objects' three-dimensional properties. Several studies confirm this view by showing the pivotal role of vision in guiding spatial judgments in other sensory modalities, such as hearing and touch (Cappagli et al., 2015; Thinus-Blanc and Gaunet, 1997; Vasilyeva and Lourenco, 2010; Vercillo et al., 2016). Vision presents some relevant advantages compared to other modalities. For instance, it allows the simultaneous perception of multiple and distal stimuli at a time (Foulke, 1982; Iachini et al., 2014; Merabet and Pascual-Leone, 2010; Pasqualotto and Proulx, 2012) and is more accurate in updating spatial information during navigation (Blasch and Welsh, 1980; Foulke, 1982; Loomis et al., 1993; Strelow, 1985).

Conversely, touch is the best sense to convey spatial information related to the size and shape of objects, but it operates only within the body's scope. Therefore, it allows spatial encoding only in the peripersonal space (Brain, 1941; M. Gori, 2015; Hall, 1966; Previc, 1998;

Rizzolatti et al., 1981). Finally, hearing can convey spatial information for near and far space both in active and passive conditions (Jacobson, 1998; Wanet and Veraart, 1985), but it is generally less accurate than vision (Kolarik et al., 2016). The main role of vision on spatial perception is to facilitate the assumption of a perspective based on externally visible landmarks (allocentric frame of reference) other than the perspective based on our body feedback (egocentric frame of reference) (Foley et al., 2015; Klatzky, 1998). Moreover, vision contributes to compensate our egocentric perspective in other senses, e.g. touch (Newell et al., 2005; Newport et al., 2002; Postma et al., 2007; Spencer et al., 1989), confirming the hypothesis that our perception is calibrated on the sense that provides the more accurate and robust information on the external objects, namely the cross-sensory calibration theory (King, 2009; King et al., 1988). Studies investigating the role of vision on spatial perception indicate that when vision is impaired, haptic and auditory spatial judgments are more biased towards an egocentric perspective, with increasing difficulties in shifting towards allocentric spatial coordinates (Cattaneo et al., 2008; Pasqualotto et al., 2013; Schmidt et al., 2013).

As a consequence, visual loss may significantly affect spatial development and possibly impair the consolidation of spatial abilities across the lifespan (Bigelow, 1996; Cattaneo et al., 2008; Koustriava and Papadopoulos, 2010; Ungar et al., 1995). Indeed, recent studies suggest that a congenital visual impairment significantly prevents visuo-motor experiences that typically guide spatial development (Gori et al., 2014; Vercillo et al., 2016). Moreover, profound and long-term visual deprivation can interfere with the consolidation of neural circuits underlying the construction of spatial representations (King, 2015; Lazzouni and Lepore, 2014). Nonetheless, despite the growing scientific interest in the role of visual experience on spatial competence, little is known about the developmental mechanisms underlying spatial development following a visual impairment or temporary deprivation. The following sections will provide an overview of scientific findings related to spatial competence in adults (Section 1.1) and in children (Section 1.2) with visual disability. It will be also provided an overview of the technological aids to support spatial perception in visually impaired individuals (Section 2) will be provided. Finally, the present doctoral thesis's objectives will be discussed within the context of current research gaps in the scientific literature on the topic (Section 3).

1.1 The impact of visual experience on spatial perception

As discussed above, compared to other sensory modalities, vision dominates spatial perception, as confirmed by paradigms creating conflicting sensory situations (Alais and Burr, 2004; Anderson and Zahorik, 2011; Bertelson and Aschersleben, 2003; Botvinick and Cohen, 1998; Flanagan and Beltzner, 2000; Zahorik, 2001). For instance, studies investigating visual-auditory conflicts, such as the ventriloquist effect (Mateeff et al., 1985; Warren et al., 1981) demonstrate that spatial resolution is higher in the visual than in the auditory system (Voss, 2016). Consequently, perceptual development, also comprising spatial development, can be altered when the visual experience is impoverished, as in the case of low vision, or missing, as in the case of blindness. Two opposing hypotheses tried to describe the effects of visual deprivation on perceptual development. While the *sensory compensation hypothesis* suggests that visual deprivation does not alter perceptual development in other sensory modalities, the *perceptual deficit hypothesis* argues that the lack of vision would cause a perceptual deficit in the intact modalities. Therefore, considering the dominant role of vision in spatial development, the first and second hypotheses would predict intact and altered spatial development in individuals with visual loss, respectively. More specifically, the sensory compensation hypothesis would lead to the conclusion that spatial development is not impaired in visually impaired individuals because intact sensory modalities refine their functional capabilities after sensory loss (Pavani and Bottari, 2011). The deficit might be compensated in specific auditory and proprioceptive tasks, e.g. azimuthal localization (Blauert, 2005; Bola et al., 2017; Lomber et al., 2010; Pascual-Leone and Hamilton, 2001; Salminen et al., 2012; Shiell et al., 2014) and relative distance discrimination (Dehaene, 2005; Ricciardi et al., 2014), or in haptic tasks, as size discrimination with a cane (Dehaene and Cohen, 2007), haptic object exploration and recognition (Hannagan et al., 2015), tactile recognition of 2D angles and gratings (Benetti et al., 2017) and immediate hand-pointing localization (MacSweeney and Cardin, 2015). The idea that residual senses compensate for the lack of vision has been further supported by cross-modal plasticity mechanisms (Kolarik et al., 2014; Schenkman and Nilsson, 2010), demonstrating that auditory stimuli activate cortical areas responsible for visual stimuli processing (Collignon et al., 2006; Collignon and De Volder, 2009; Thaler et al., 2014). Conversely**,** the perceptual deficit hypothesis would lead to the conclusion that spatial development is impaired in visually impaired individuals because intact sensory modalities cannot process spatial information in absence of the leading sense, namely vision. Such hypothesis has been confirmed by studies demonstrating that visually impaired individuals present spatial deficits for auditory localization in the vertical plane (Voss et al., 2015), auditory bisection (Gori et al., 2014), vertical localization (Lewald, 2002; Zwiers et al., 2001) and absolute distance discrimination (Andrew J Kolarik et al., 2013). Similar impairments have been shown in the tactile domain, such as haptic orientation discrimination (Postma et al., 2008), visual spatial imagination (Noordzij et al., 2007), updating of spatial information (Pasqualotto and Newell, 2007) and rotation of object arrays (Ungar et al., 1995) tasks. Therefore, the perceptual deficit hypothesis would support the general idea that auditory and tactile representations of space are constantly and continuously refined by visual experience (King, 2009). Very recently, a third hypothesis has been proposed with the main aim to reconcile the contrasting findings related to the presence of enhancements or impairments following visual deprivation. The visual calibration hypothesis (Eimer, 2014; Gori et al., 2012b, 2010; Gori, 2015) postulates that visual loss or impoverishment significantly affects spatial abilities in the other modalities (hearing and touch), mainly because during development vision calibrates other senses in processing spatial information. This hypothesis is based on the idea that our perception is calibrated by the sense that provides the more accurate and robust representation of events. Therefore, since vision is the best modality to process spatial information, vision would be the teaching modalities for spatial perception. Such hypothesis has been confirmed by several behavioral studies showing that the absence of vision from birth determines auditory and proprioceptive spatial impairments in the blind population (Amadeo et al., 2019; Cappagli et al., 2015; Cappagli and Gori, 2019, 2016; Gori et al., 2020a, 2017). Moreover, the idea that vision calibrates hearing for spatial perception has been further supported by neurophysiological studies demonstrating that visual experience influences the development of auditory spatial properties of neurons in the superior colliculus (King, 2009; King et al., 1988).

In the following sections, I will deepen the maturation process of spatial coding skills when visual experience is prevented in adults (Section 1.1.1) and compare the developmental trends of spatial abilities in children with typical and atypical visual experience (Section 1.1.2).

1.1.1 Spatial competence in adults with visual impairments

Sighted individuals strongly rely on visual feedback when asked to perform spatial judgments and are biased towards visual feedback when asked to localize objects within the auditory space (Campus et al., 2019; Barry E. Stein and Meredith, 1993). Such evidence indicates that vision is the leading sense to promote spatial development. Consequently, we might expect to see a worse spatial performance in individuals affected by a visual disability across the lifespan. Nonetheless, contrasting results indicate that visually impaired individuals present an impaired performance only for specific spatial tasks, possibly indicating that visual experience is necessary only in some conditions. For instance, sighted individuals tend to perform worse than blind individuals in an auditory localization when blindfolded (e.g., (Andrew J. Kolarik et al., 2013; Voss et al., 2004)), especially in the case of sounds located in the horizontal plane (Abel et al., 2002; Tabry et al., 2013). Other studies have found similar results for static sound localization and spatial processing of two sounds in the horizontal plane (e.g., (Doucet et al., 2005; Gougoux et al., 2004; King and Parsons, 1999; Lessard et al., 1998; Lewald, 2007; Roder et al., 1999)) as well as in a minimum audible angle task (Gori et al., 2014; Hüg et al., 2014; Vercillo et al., 2015; Voss et al., 2004). Enhanced spatial performance in the blind population is probably due to changes in the auditory pathway (Elbert et al., 2002; Korte and Rauschecker, 1993; Petrus et al., 2014) or in the recruitment of the visual cortex (e.g., (Gougoux et al., 2005; Poirier et al., 2005; Renier and De Volder, 2005; Striem-Amit and Amedi, 2014; Weeks et al., 2000)). Moreover, we might hypothesize that auditory and tactile spatial skills are refined and respective cortical areas more reactive due to use-dependent plasticity, as has been observed for heightened tactile acuity with prolonged experience in reading Braille (Wong et al., 2011). In contrast with the previous findings, other studies indicate that spatial performance is impaired in blind when asked to judge auditory distance (Cappagli et al., 2015), probably because they tend to overestimate distances in the near space and underestimate distances in the far space (Kolarik et al., 2017). Moreover, other studies demonstrated that visual deprivation affects specific auditory spatial abilities, such as auditory bisection (Gori et al., 2014), vertical localization (Lewald, 2002; Zwiers et al., 2001) and absolute distance discrimination (Kolarik et al., 2013). Visual deprivation also impacts on tactile spatial abilities, such as haptic orientation discrimination (Postma et al., 2008), visual spatial imagination (Noordzij et al., 2007), representation and updating of spatial information

(Pasqualotto and Newell, 2007) and rotation of object arrays (Ungar et al., 1995). Impoverished spatial performance after visual loss is supported by neurophysiological evidence showing altered auditory spatial learning of cortical maps in the superior colliculus (King and Carlile, 1993; Knudsen and Brainard, 1991; Withington, 1992) in visually deprived animals. Such evidence that non-visual spatial maps are continuously refined by visual experience (King, 2009).

Overall, research studies investigating the role of visual experience on spatial development suggest that, whereas blind adults show impaired spatial performance when referring to external (i.e., allocentric) landmarks, they showed superior spatial performance when relying on their bodily (i.e., egocentric) perspective (Andrew J. Kolarik et al., 2013; Vercillo et al., 2018). Indeed, it has been shown that head motion compromises the detection of auditory moving targets in early blind individuals, with a localization bias towards the direction of the head movement, suggesting a strong reliance on body-centered frames of reference (Vercillo et al., 2017), in contrast with sighted individuals (Finocchietti et al., 2015b; Lewald, 2013; Zwiers et al., 2001).

Moreover, other evidence indicates that several factors need to be considered when assessing spatial performance in the blind. For instance, Vercillo and colleagues (2015) demonstrated that spatial abilities are preserved in blind individuals trained in echolocation, namely a technique that allows humans to detect objects in their environment by sensing echoes from those objects by actively creating sounds. Moreover, it has been shown that the onset of blindness can strongly influence the consolidation of spatial coding skills in adulthood. Indeed, individuals who lost vision later in life after experiencing a normal visual development show equal or even better performance than sighted participants in several auditory spatial tasks (Cattaneo et al., 2008; Hart and Moore, 1973; Holmes and Spence, 2004; Andrew J Kolarik et al., 2013). From the growing body of studies investigating the role of vision on spatial perception, visual experience has a different impact on the development of spatial competencies depending on the task proposed, resulting in enhanced or impaired skills when absent. Moreover, very few studies investigated the time course of spatial abilities in visual disabilities, despite its importance for early intervention purposes.

1.1.2 Spatial competence in children with visual impairments

The first pioneering theory related to the typical development of spatial competencies in humans has been proposed by Piaget and colleagues (Piaget et al., 1960; Piaget and Inhelder, 1967), assuming that spatial consciousness gradually improves with age and builds up a whole sensorimotor experience of the environment. Starting from 3 months of age, infants are capable of distinguishing above vs. below and left vs. right (Quinn, 1994; Quinn et al., 1996), while at five months, they begin to code spatial object dimensions such as height (Baillargeon, 1987; Baillargeon et al., 1985; Baillargeon and DeVos, 1991), distance location (Newcombe et al., 1999), and angles (Lourenco and Huttenlocher, 2008). Concerning the development of spatial coordinates, it has been shown that 9-months infants can rely on their body to update objects' position in space. Therefore, their spatial coordinates system is mainly egocentric (Landau et al., 1984; Rieser and Heiman, 1982). Research has shown that only later in the development they will be able to shift their attention from spatial relations based on their body (egocentric frame of reference) towards spatial relations based on external objects (allocentric frame of reference). Indeed, several studies demonstrated that adjacent landmarks embedded in the environment (Lew et al., 2000) represent a reliable spatial strategy starting from 12 months of age, with a further improvement in spatial allocentric performance between 16 and 36 months (Newcombe et al., 1998). At around 18–24 months of age, toddlers refine their spatial competence by using allocentric geometrical cues such as shape to orient themselves in space (Hermer and Spelke, 1996, 1994). Conversely, the ability to integrate the two complementary reference frames (egocentric and allocentric) in a common spatial reference system does not emerge before 8 years of age, when children alternate both egocentric and allocentric strategies instead of combining them, as adults usually do (Nardini et al., 2008). It has been argued that the emergence of allocentric coding in the form of cue learning might derive from the onset of crawling at around 8–9 months. Indeed, crawling allows infants to experience changes in the external world and supports the shifting from a body-oriented localization of objects to one based on the use of environmental landmarks (Aytekin et al., 2008; Bremner et al., 2008).

Moreover, research on auditory spatial perception has shown that sighted infants improve their ability to turn the head toward a sound since birth (Muir and Field, 1979). At six months of age, infants can code the location of sonorous objects in space within 13-19 degrees spatial angles (Ashmead et al., 1989; Morrongiello et al., 1998). Following these findings, it has been shown that sighted infants rely on auditory cues in the absence of visual feedback (Clifton, 1992; Clifton et al., 1991; Litovsky and Clifton, 1992; Morrongiello et al., 1998; Perris and Clifton, 1988), suggesting that the concept of auditory space is well consolidated at this developmental stage. Nevertheless, Gori and colleagues (2012) showed that vision dominates spatial hearing until 12 years of age for complex tasks such as auditory bisection and that no optimal sighted-like integration capabilities are observed.

Although the development of spatial competence has been extensively studied in sighted infants, less effort has been spent in understanding how the sense of space develops in children with visual impairment (Cappagli and Gori, 2019). Since it has been shown that spatial representation emerges gradually thanks to the reciprocal influence between visual and motor feedback (Bremner et al., 2008), and altered visual experience during growth could determine auditory and haptic impairments due to the lack of visuo-motor correspondences (Fraiberg, 1977; Landau et al., 1984; Warren, 1977). For instance, while sighted children typically start to perform first individual actions and navigation from 12 months, blind children without cognitive and motor impairments start to walk at about 30-32 months of age (Pérez-Pereira and Conti-Ramsden, 2005). Such motor delay is caused by the absence of visual feedback that prevents visually impaired infants from reaching several motor milestones, e.g., rolling, crawling, standing, and balancing (Hallemans et al., 2011; Houwen et al., 2009), confirming the fundamental role played by visuo-motor experience for the development of self-concept. Research related to the development of auditory spatial skills in the absence of vision provided contrasting results. Indeed, it has been shown that visually impaired children can discriminate differences in sound localization in the horizontal and vertical plane and reach or walk towards sound source (Ashmead et al., 1998).

Conversely, other studies suggested that infants and children with severe congenital blindness are severely delayed in the development of sound localization abilities (Cappagli et al., 2015; Cappagli and Gori, 2016; Fraiberg, 1977; Vercillo et al., 2016) and motor responses to sounds (Adelson and Fraiberg, 1974; Fraiberg et al., 1966). For instance, while sighted children start to reach sonorous targets at around five months, blind children show the same ability only after the first year of life (Bayley, 1993). Furthermore, blind children perform worse than sighted children in several auditory task, e.g. bisection and minimum audible angle tasks (Vercillo et al., 2016) and audio depth (Cappagli et al., 2015). Similarly, the ability to detect auditory moving targets is impaired in visually impaired individuals, especially in blind compared to low vision children (Cappagli et al., 2015; Fraiberg, 1977). Interestingly, the spatial performance of blind children is comparable to that of blind adults, suggesting that the strong reliance on nonvisual cues may help to solve a certain variety of auditory motion detection/lateralization tasks (Adelson and Fraiberg, 1974; Fraiberg et al., 1966).

Overall, all these findings suggest that a multimodal perception of space is not fully developed until later in life in case of visual loss or impoverishment (Gori, 2015). Moreover, depending on the spatial ability considered, the early or late emergence or the visual impairment can have profound consequences for the development of spatial skills (Shiell et al., 2016). Consequently, early intervention specifically focused on activities fostering the development of spatial perceptual skills and motor abilities would help visually impaired children to overcome perceptual delays and deficiencies caused by the absence of visual inputs.

1.2 Technological aids to enhance spatial representation in the absence of vision

In the previous sections, an overview of research studies investigating the impact of altered visual experience on spatial development and consolidation has been presented. Given that visually impaired individuals manifest developmental delays and impairments in both auditory and haptic domains, the design of rehabilitation tools to support spatial competence would be a need. The term "assistive technology" has been used to define technological systems that satisfy users' needs in terms of assistance by assuring the enhancement of users' abilities and their safety and well-being (Csapó et al., 2015). Technological systems for visually impaired individuals are mainly categorized based on the sensory signal (i.e., audition or touch) used to substitute the absent sensory information (i.e., vision) for daily activities (Cappagli and Gori, 2019; Gori et al., 2012b; Richardson et al., 2019). The most effective systems developed to date are defined as Sensory Substitution Devices (SSDs), i.e. technological aids that convert visual stimuli into stimuli accessible to another sensory modality (e.g., hearing or touch). SSDs are dedicated to converting the spatial information about the position, size, shape, color, and motion of visual objects into auditory or tactile information (Gori et al., 2016; Hamilton-Fletcher and Ward, 2013).

Specifically, SSDs developed for visually impaired individuals are categorized into two main families: i) visual-to-tactile devices; ii) visual-to-auditory devices (Proulx and Harder, 2008). Technically, the system includes a sensor that converts light energy (visual stimuli), sound, and mechanical into electronic signals to provide stimulation in terms of sound energy (auditory stimuli, as in the case of visual-to-auditory devices) or mechanical energy (tactile stimuli, as in the case of visual-to-tactile devices) (Lenay et al., 2003). The first visual-to-tactile device was developed in 1969 and named Tactile Vision Sensory Substitution (TVSS) device (Bach-Y-Rita et al., 1969). The system was provided with a television studio camera, adaptable to the user, connected to vibrating solenoids, positioned in the back of a dentist's chair, arranged in a matrix that resembled the camera's pixels. The developers presented improved versions of the TVSS device, introducing electro-tactile stimulation. Moreover, they lead the development of the Tongue Display Unit (Sampaio et al., 2001), namely an SSD that converts 2D greyscale images into a spatialized pattern of electro-tactile stimulation on the tongue in real-time. More recently, another tongue-stimulator was created, called the BrainPort, even though no visual acuity improvements due to its use were recorded (Nau et al., 2013; Stronks et al., 2016). Moreover, vibrotactile technologies have improved with the introduction of three-dimensional (3D) cameras, mobile computer processing and a single-unit wearable vest (Ertan et al., 1998; Jones et al., 2004; Rochlis, 1998; Spanlang et al., 2010), e.g. the VibroVision, equipped with a series of vibrating motors arranged on the users' abdomen (Wacker et al., 2016). Concerning visual-to-auditory devices, despite the starting prototypes were created much earlier than visual-to-tactile devices (e.g., Noiszewski's Elektroftalm in 1897 – (Starkiewicz and Kuliszewski, 1963)), the first device that acquired relevance for scientific purposes was 'the vOICe' (Meijer, 1992), namely a device provided with a software that converts 2D greyscale images into soundscapes played through headphones. The vOICe reproduced the horizontal axis through stereo playback and temporal information scanning from left to right, the vertical axis through pitch changes (i.e., louder volumes for brighter images), and brightness through volume (i.e., higher pitches for higher locations). The vOICe has been widely tested in experimental contexts and it is still considered one of the higher resolution auditory substitution devices (Haigh et al., 2013; Striem-Amit et al., 2012c). More recent SSDs have been developed to provide 3D information for localizing individual objects, segmenting their shape, and navigating (Caraiman et al., 2017; Dunai et al., 2013; Fristot et al., 2012; Spagnol et al., 2017; Stoll et al., 2015). The process of 3D sonification of objects' spatial location is referred to as a 'virtual acoustic space' (Eckert et al., 2018; González-Mora et al., 2006, 1999; Rodríguez-Hernández et al., 2010), with the 'Synaestheatre' as the main example (Hamilton-Fletcher et al., 2016). The spatialized fully-3D sounds produced by the Synaestheatre are updated in real-time and, similarly to VibroVision, the azimuth and elevation of sounds are conveyed spatially.

Nonetheless, despite the increasing scientific effort in developing novel technological assistive aids to address visually impaired population's needs, several limitations in their use have been pointed out (Cappagli and Gori, 2019; Gori et al., 2016). The most striking limitations that might determine low acceptance rate in adults and low adaptability in children are reported:

- invasiveness: SSDs can be invasive since they need to be positioned on crucial body parts (e.g., ears or mouth) or to be transported (e.g., in backpacks), limiting users' perceptual functions and navigation abilities due to weight and size;
- extensive training: SSDs usually require long periods of training since the user must learn how to interpret the output of the device, which is not immediate (e.g., the correspondence of sound loudness to pixel brightness in the vOICe (Striem-Amit et al., 2012a));
- high cognitive load: SSDs need the user to employ high attentional resources for all the time they use the device;
- absence of clinical validation: the majority of SSDs remain prototypes without reaching the market, principally because they are not validated on large sample patients under standardized clinical trials;
- artificiality: SSDs expect the user to convert a physical visual stimulus into a sound (in the case of visual-to-auditory SSDs) or a physical feeling (in the case of visual-to-tactile SSDs) through an artificial transformation code that does not comprehend an action-perception link.

Moreover, SSDs have been mainly tested in adults (Maidenbaum et al., 2014), but they have never been tested in children, especially because of their overwhelming cognitive load.

Concerning other assistive solutions aimed at supporting spatial skills, the most developed solutions to date consist in technological canes and robots for mobility, which support visually impaired individuals during navigation. A review by Cuturi and colleagues (2016) presented the most relevant assistive technologies to guide visually impaired people in locomotion, generally provided with sensors, actuators and displays mounted on an external and independent support, which usually moves on wheels. Technological canes and navigation robots acquire information from mainly indoor environments and translate it into audio-tactile feedback, even though a passive guidance might lead to a possible reduction of independent orientation. Among technological aids for navigation, visually impaired children might use three types of devices: a) powered mobility devices, that exploit legs or the upper body movements to be driven; b) pre-canes, that precede the use of the white cane; c) virtual reality technology, that aim to develop spatial skills to improve outdoor mobility in a safe but quite realistic environment.

The main limitations observed in technological canes and robots for mobility are reported:

- low attention on children;
- lack in the study of the brain mechanisms that subtend the deficit for technological development;
- little testing on users;
- substitutive and not rehabilitative systems;
- absence of specific certification procedures.

Nonetheless, technological solutions for visually impaired children are gaining interest since cortical plasticity is maximal in the first year of life. Moreover, technological development should be based on multimodal stimulation, which has been shown to be more effective than unimodal stimulation in conveying spatial information (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008). From a general point of view, every technological development should start from the neuroscientific understanding of the mechanisms underlying visual impairment, and the transmitted information has to be associated with user capabilities. Newly developed technological aids for visually impaired individuals should foresee the early inclusion of such systems in rehabilitation programs starting from the first years of life. These devices' goal is to provide an immediate benefit in terms of quality of life and an important opportunity for children to develop perceptual and cognitive abilities by compensating for the sensory deprivation.

1.3 Objectives of the doctoral thesis

Chapter 1 illustrates research studies highlighting the relevant role of vision in calibrating other senses to perceive spatial information (Cappagli et al., 2015; Thinus-Blanc and Gaunet, 1997; Vercillo et al., 2016). Several studies have demonstrated that vision provides the most detailed spatial information based on the allocentric or object-centered frame of reference (e.g., external to the observer’s body) (Foley et al., 2015; Klatzky, 1998) compared to other senses, which are mainly based on egocentric or body-centered frames of reference (e.g., referred to the observer’s body) (Newell et al., 2005; Newport et al., 2002; Postma et al., 2007; Spencer et al., 1989). Therefore, visual impairments can increase the reliance on egocentric spatial cues, with a negative impact on the development and consolidation of allocentric spatial coordinates (Cattaneo et al., 2008; Pasqualotto et al., 2013; Schmidt et al., 2013) (Bigelow, 1996; Cattaneo et al., 2008; Koustriava and Papadopoulos, 2010; Ungar et al., 1995). Despite the consistent amount of scientific studies assessing the influence of visual deprivation on spatial development, to date, very few studies investigated the mechanisms underlying the perceptual enhancements and deficits associated with visual impairment. Moreover, experimental systems' paucity to quantitatively assess unisensory and multisensory spatial skills and the lack of technological systems to support spatial development in visually impaired children needs to be addressed.

The present thesis has two main aims: i) increasing scientific knowledge about the role of visual experience on spatial perception (scientific objective); ii) developing new experimental paradigms and technological devices to assess and train spatial skills in individuals with visual disabilities (technological objective). The main scientific objective of the thesis is to investigate the developmental and consolidation process of spatial representation in children and adults with different visual experiences since birth. Moreover, this thesis aims to assess whether other sensory modalities (hearing and touch) predominantly based on external (allocentric) or body-centered frames of reference can be exploited to explore different objects’ spatial features. Specifically, in the present thesis, I designed novel experimental paradigms to investigate the role of visual experience on spatial competence in children with a residual or total absence of vision and adults with temporal visual deprivation. To reach this objective, we assessed children and adults’ capabilities to integrate complementary reference frames based on body and environmental landmarks. Overall, the results obtained will demonstrate whether the absence of would compromise auditory and haptic spatial skills residual sensory modalities (e.g., hearing and touch) or whether compensatory mechanisms emerge following visual impairment. Recently, there has been a growing development of technological aids to compensate spatial deficits caused by the absence of visual inputs by relying on auditory and tactile feedback. To date, Sensory Substitution Devices (SSDs) and assistive technologies for mobility (Cuturi et al., 2016) provide the most effective way to overcome visual impairment by converting visual stimuli into stimuli accessible to another sensory modality (e.g., hearing or touch) (Amedi et al., 2007; Bach-y-Rita and Kercel, 2003; Gori et al., 2016; Hamilton-Fletcher and Ward, 2013; Meijer, 1992; Proulx and Harder, 2008).

Nonetheless, despite the technological effort put in the development of novel assistive aids for visually impaired individuals, limitations due to low user acceptance (Cappagli and Gori, 2019; Gori et al., 2016), absence of assessing purposes and poor rehabilitative intents (Gori et al., 2016) have emerged. The main technological objective of the thesis is to develop and validate novel rehabilitation devices to train spatial skills in visually impaired individuals and assess the potential benefit deriving from the use of such devices in the clinical context meant. Specifically, in the present thesis, I worked on the development of the hardware and software components of an interactive, multisensory platform (iGYM) comprising three innovative technological solutions (i.e., TechARM (Schiatti et al., 2020), TechPAD, TechMAT). Moreover, I validated using a rehabilitative device called ABBI (Audio Bracelet for Blind Interaction; see (Finocchietti et al., 2015c)) to train auditory and proprioceptive spatial skills in adults with and without visual impairment in auditory and proprioceptive spatial skills.

Overall, the results obtained from this thesis will improve knowledge on methodologies to quantitatively assess spatial performance in case of unisensory and multisensory events, and to help visually impaired individuals in specific trainings for the rehabilitation of spatial coding skills by relying on residual sensory modalities.

Chapter 2

Spatial coding skills with and without visual feedback

Chapter 1 summarized the main research findings related to the role of vision and multisensory experience on spatial development and the main technological outcomes to date to support visually impaired individuals by substituting visual loss with other senses, i.e. hearing and touch. Overall, such findings indicate that visual experience facilitates the acquisition of spatial capabilities. Most of all, compared to hearing and touch, vision allows to encode spatial properties of perceptual events based on environmental landmarks, which are independent of body perspective and thus permit a more comprehensive representation of spatial information. Therefore, Chapter 2 aims to improve knowledge on the development and consolidation of spatial coding skills and the impact of visual loss on the ability to rely on external instead of bodily frames of reference.

2.1 Introduction

The ability to locate and identify objects in space has been extensively considered a milestone for spatial development (Cappagli and Gori, 2019; Lew et al., 2000; Vasilyeva and Lourenco, 2012). The cognitive representation of space is built upon the spatial perspective assumed, namely the frame of reference that allows us to keep track of and continuously update objects' position in the surrounding. The egocentric or subject-centered perspective describes an object by referring to the perceiver's own body, while the allocentric or object-centered frame of reference is based on external landmarks positioned in space (Foley et al., 2015; Klatzky, 1998). The ability to integrate different representations of space based on egocentric and allocentric coordinates allows to encode an event's spatial properties. Several studies have shown that egocentric and allocentric reference systems coexist until 6 years of age (Nardini et al., 2006; Newcombe and Huttenlocher, 2003). The development of an allocentric representation based on external references instead of the observer's position takes place using adjacent (cue learning) or distal (place learning) landmarks. Indeed, it has been demonstrated that children with typical development attempt to rely on adjacent landmarks (cue learning) to find non-visible targets (Acredolo, 1981; Piaget and Inhelder, 1967) and start to rely on distal landmarks (place learning) at 12 months of age (Lew et al., 2000). At 24 months of age, toddlers show the ability to rely on distal cues (Newcombe et al., 1998), consolidating the consciousness of relations between distal landmarks throughout childhood (Nardini et al., 2009; Overman et al., 1996; Rieser and Rider, 1991; Vasilyeva and Lourenco, 2012). Nonetheless, the ability to efficiently integrate egocentric and allocentric frames of reference starts after six years of age and is still not mature until eight years of age (Bullens et al., 2010; Nardini et al., 2008, 2006). The ability to update spatial representation by combining body- and object-centered landmarks depends on environmental changes within the switching-perspective skills (Burgess, 2006; Cornoldi et al., 1991; Harris et al., 2012; Nadel and Hardt, 2004; Vecchi et al., 2004). The consolidation of spatial frames of reference typically happens in adulthood, when individuals employ spatial strategies based on the integration of egocentric and allocentric frames of reference (Nadel and Hardt, 2004).

Empirical evidence suggests that allocentric spatial coding is promoted by visual experience across development (Pasqualotto et al., 2013; Thinus-Blanc and Gaunet, 1997) and by the ability to combine multiple sensory inputs of the same object (Nardini et al., 2009; Vasilyeva and Lourenco, 2012). Therefore, the visual loss might impair the integration of egocentric and allocentric perspectives in other senses, e.g. touch (Newell et al., 2005; Newport et al., 2002; Postma et al., 2007; Spencer et al., 1989), according to the cross-sensory calibration theory (King, 2009; King et al., 1988). It has been widely demonstrated that vision plays a relevant role in the acquisition of spatial knowledge and it is considered the leading sense in the development of an allocentric spatial coding system (Giudice, 2018; Schinazi et al., 2016; Thinus-Blanc and Gaunet, 1997). Indeed, vision seems to calibrate spatial representation in the other non-visual modalities, such as hearing and touch (Eimer, 2004; Newell et al., 2005). Moreover, vision constitutes the most important sensory input to comprehend the spatial properties of objects (Thinus-Blanc and Gaunet, 1997), such as the objects' shape (Erdogan and Jacobs, 2017; Milner, 1974; Peelen et al., 2014; Pietrini et al., 2004). As a consequence, visual loss may significantly affect an adequate spatial representation of the external world (Bigelow, 1996; Cattaneo et al., 2008; Koustriava and Papadopoulos, 2010; Ungar et al., 1995). In line with this view, it has been demonstrated that visually impaired adults tend to assume an egocentric perspective to code space, probably due to the use of residual sensory modalities mainly based on body landmarks, i.e. touch (Cattaneo et al., 2008; Pasqualotto et al., 2013). Furthermore, the absence of vision negatively impacts on the ability to solve spatial tasks that rely on allocentric cues (Cattaneo et al., 2008; Iachini et al., 2014; Merabet and Pascual-Leone, 2010; Millar, 1994; Pasqualotto and Proulx, 2012; Schmidt et al., 2013; Thinus-Blanc and Gaunet, 1997), and to combine different reference frames in response to environmental changes – i.e., switching-perspective skills (Burgess, 2006; Cornoldi et al., 1991; Harris et al., 2012; Nadel and Hardt, 2004; Vecchi et al., 2004). Conflicting results indicate that visually impaired individuals can rely on allocentric frames of reference, but they might also remain anchored to an egocentric perspective, depending on the spatial task administered (Gaunet et al., 2007; Gaunet and Rossetti, 2006; Giudice et al., 2011; Rossetti et al., 1996). Concerning switching-perspective abilities, it has been shown that visually impaired children manifest difficulties in performing mental rotation tasks, for instance, when asked to mentally rotate their spatial perspective without any physical change (Huttenlocher and Presson, 1973; Koustriava and Papadopoulos, 2012; Millar, 1976). Although audition seems to provide effective spatial cues in processing spatial properties of objects, such as shape, in absence of visual inputs (Bizley and Cohen, 2013; Carello et al., 1998) , a multisensory description of space is mostly mediated by visual spatial coordinates, that link inputs from multiple sensory modalities (Bremner et al., 2012; Pouget et al., 2002). Röder and colleagues (2012) suggested that the increasing dominance of vision across development fosters the assumption of a visual allocentric perspective to encode the environment (see also Warren and Pick, 1970). Following this view, they affirmed that the lack of visual feedback is detrimental for the development of a multisensory approach based on the use of external landmarks.

To sum up, several pieces of evidence suggest that sighted and visually impaired individuals differently develop spatial reference systems across development, mainly due to the absence of visual feedback and the impossibility to rely on multisensory integration for spatial development. Nonetheless, it is still unclear when and how the acquisition of the ability to switch from egocentric to allocentric frames of reference emerges across childhood, in case of partial (low vision) or total (blindness) absence of vision. Furthermore, little is known about the ability to discriminate spatial properties of known objects without any visual cues. Chapter 2 aims at investigating whether and how visual feedback affects the spatial perception of the environment and the development and consolidation of spatial coding abilities from childhood until adulthood. In this chapter, I also propose novel experimental paradigms to assess whether, in the absence of vision, other sensory modalities, e.g. touch and audition, would be reliable to build maps based on external rather than bodily spatial frames of reference and to discriminate typically visual spatial features of the environment. More in detail, in the following sections, I will further investigate the following aspects: effects of partial loss of vision, i.e. low vision, on the development and integration of different spatial coordinates systems (Section 2.2); effects of a total loss of vision, i.e. blindness, on the development and integration of different spatial coordinates systems (Section 2.3); effects of substituting the visual with the auditory input to convey spatial information such as shape contours (Section 2.4).

2.2 Visuo-spatial development in low vision children

It has been widely shown that visual experience plays a critical role in encoding space based on allocentric or object-centered spatial coordinates. Nonetheless, very little is known about allocentric spatial coding abilities when visual experience is impoverished, as in low vision. A study conducted by Ochaíta and Huertas (1993) indicates that sighted children acquire a coherent sense of space at 14 years of age while visually impaired children at 17 years of age, suggesting a developmental delay following visual deprivation. This can be explained by the fact that visual deprivation results in a lack of sensorimotor (visuo-motor) feedback that in turn can delay locomotor development (Fazzi et al., 2002; Fraiberg, 1977; Landau et al., 1984), which has been indicated as a fundamental step for spatial development (Bremner et al., 2008). Indeed, a delay in locomotor development might cause children to accumulate much less multisensory spatial experience related to the surrounding objects, determining their difficulty in perceiving objects other than from their egocentric perspective. Other studies indicate that visually impaired children manifest deficits in performing mental rotations of the self (perspective-taking; (Huttenlocher and Presson, 1973; Koustriava and Papadopoulos, 2012; Millar, 1976; Papadopoulos and Koustriava, 2011) and objects/configurations (Huttenlocher and Presson, 1973; Papadopoulos and Koustriava, 2011; Penrod and Petrosko, 2003), further confirming the role of visual feedback on spatial representation dependent on allocentric cues

(Cappagli et al., 2015; Cappagli and Gori, 2019, 2016; Koustriava and Papadopoulos, 2012; Papadopoulos and Koustriava, 2011).

To date, it is still unclear whether the acquisition of allocentric spatial skills during childhood might be affected by partial loss of vision. In the present study, we assessed whether the ability to switch from egocentric to allocentric spatial coordinates is compromised by an impoverished visual experience during childhood (namely low vision) to understand whether vision is necessary to develop switching-perspective abilities during childhood. We hypothesized that children with an atypical visual experience during development would rely more on body-centered cues and then show difficulties in tasks based on allocentric perspectives. To test our hypothesis, we compared children with typical and atypical visual experience in switching from an egocentric to an allocentric representation of visual space. Visually impaired and sighted participants were asked to reproduce a spatial configuration of visual stimuli from different spatial perspectives related to egocentric or allocentric frames of reference.

Sample

Sighted and visually impaired children between four and nine years of age were enrolled in the study. Sighted children were recruited from local schools, visually impaired children were recruited from a local hospital (IRCCS Mondino Foundation, Pavia, Italy) based on their visual acuity (VA). To define the visual deficit, we exploited specific tests following the "International Statistical Classification of Diseases and Related Health Problems" (World Health Organization, 1993), which defines moderate to severe visual impairment as a condition characterized by VA comprised between 0.5 and 1.3 LogMAR (Logarithm of the Minimum Angle of Resolution, defined as log10($M_{inimum}A_{ngle}R_{esolution}$)). We recruited visually impaired children with best-corrected binocular VA in the range 0.5–1.3 LogMAR, at a testing distance of 3 m (see Table 2.1 for clinical details of participants). We evaluated the cognitive development of visually impaired children with the verbal scale of the "Wechsler Preschool and Primary Scale of Intelligence" (Wechsler, 2012) and the "Wechsler Intelligence Scale for Children" (Wechsler, 2014), according to their chronological age. Only children presenting adequate cognitive development were recruited. Neither visually impaired nor sighted children reported additional sensory, musculoskeletal, neurological disabilities, or impairments related to color discrimination. Twenty-seven sighted (mean age: 6.56 ± 1.80 years) and fifteen visually impaired (mean age: 6.33 ± 1.72 years) children participated in the study. Both visually impaired and sighted participants were divided into three groups, based on their age range: 4-to-5 years old (five visually impaired, nine sighted), 6-to-7 years old (six visually impaired, ten sighted), and 8-to-9 years old (four visually impaired, eight sighted). The study was approved by the local Ethical Committee, and written informed consent was provided by participants' parents, in accordance with the Declaration of Helsinki. The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.62 (Partial eta squared $\eta^2_p = 0.72$; see Ruotolo et al., 2015);
- α err. prob. = 0.05;

Participant	Age range	Pathology	Visual Acuity (LogMAR)
#1	4-5	Left Micropthalmia & Bilateral Coloboma	1.00
#2	4-5	Nystagmus	1.00
#3	4-5	Retinal Dystrophy	1.00
#4	6-7	Retinopathy	1.30
#5	8-9	Microphtalmia	1.00
#6	6-7	Aniridia	1.30
#7	6-7	Nystagmus	1.00
#8	8-9	Retinal Dystrophy	1.00
#9	4-5	Albinism	0.82
#10	6-7	Bilateral Micropthalmia & Coloboma	1.30
#11	4-5	Optic Nerve Hypoplasia	1.30
#12	8-9	Retinal Dystrophy	0.82
#13	6-7	Nystagmus	0.50
#14	8-9	Optic Nerve Hypoplasia	1.00
#15	6-7	Retinopathy	1.00

- power (1-β err. prob.) = 0.95.

TABLE 2.1 Clinical details of visually impaired participants (N = 15).
The table shows the age range at test, the pathology, and visual acuity (VA) expressed in LogMAR scale at a distance of 3 m of visually impaired participants.

Task and procedure

Participants sat in the experimental room with the setup positioned in front of them on a table. The setup consisted of two 30 x 30 cm plastic boards, whose layout represented a grid with intersecting embossed straight vertical and horizontal lines used to separate boxes, on which colored coins (red, blue, and yellow) were positioned (Figure 2.1A). The boards were realized in such a way that children with visual impairment could visually discriminate stimuli by relying on high contrast colors (colored coins on high contrast background). Before the beginning of the task, the experimenter showed the participant a sample of configuration with an increasing number of coins to let the child familiarize with the task. The task procedure comprised two phases: (a) a demonstration phase, during which the experimenter presented a configuration of coins on his/her own board and allowed the participant to visually explore it; (b) a reproduction phase, during which the participant was asked to reproduce on his/her own board the configuration of the coins shown in (a). Before starting with (a), the participant was asked to assume one out of four different spatial positions and maintain the same position until (b). The participant could assume four spatial which defined the four conditions of the switching-perspective task: (1) egocentric condition, with the participant sitting next to the experimenter (0 rotation degrees) and the two boards lying next to each other (Figure 2.2A); (2) egocentric condition, with the participant sitting next to the experimenter (0 rotation

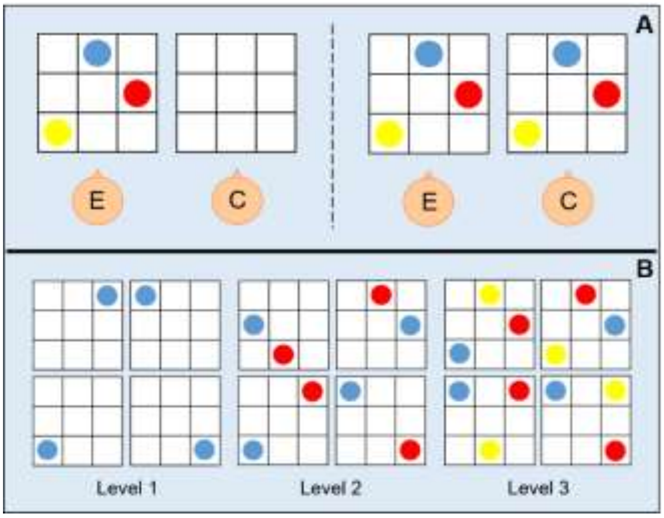

Figure 2.1 Setup and protocol of the visual switching-perspective task.
(A) Procedure for the switching-perspective task. On each trial, the experimenter (E) show to the child (C) one out of twelve possible configurations of colored coins on a plastic board made of nine boxes (left panel) and immediately after the child is asked to reproduce the same configuration on his own plastic board in front of him (right panel). **(B)** Trials for each condition of the task. The switching-perspective task comprises 48 trials that differ with respect to the level of difficulty, namely to the number of coins that constitute the configuration to be reproduced (from one to three coins respectively for the easiest and the hardest levels).

degrees) and the two boards lying one above the other (Figure 2.2C); (3) allocentric condition, with the participant sitting rotated 90 degrees to the experimenter position and the boards positioned in front of them (Figure 2.2B); (4) allocentric condition, with the participant sitting rotated 180 degrees to the experimenter position and the boards positioned in front of them (Figure 2.2D). During both phases, participants were allowed to look at the experimenter’s configuration as many times as they needed to reproduce it. Depending on the number of coins in the configuration, the task assumed three levels of difficulty (Figure 2.1B): (1) one coin, for the simplest level; (2) two coins for the intermediate level; and (3) three coins, for the hardest level. Configurations were presented to the participant in random order concerning the level of difficulty. The task procedure comprised two blocks of trials, and each block comprised one egocentric configuration and one allocentric configuration to randomize the presentation of egocentric and allocentric spatial positions (Figure 2.2, left panel: positions (1) and (3); right panel: positions (2) and (4)). The total amount of trials performed by each participant was 48 (twelve trials per four spatial positions, four trials for each level of difficulty). The whole experiment was performed on the same day in about 1 hour, and short breaks were allowed at any time during the session.

Data analysis and statistics

The accuracy in the task was measured to quantify the spatial ability to switch from an egocentric to an allocentric frame of reference in children with and without visual impairment. We computed a correctness score, as follows:

$$CS = \frac{\sum_{i=1}^{N} ncr}{N} \quad , \tag{1}$$

where CS stands for "Correctness Score," ncr stands for the number of correct responses for each of the four task conditions defined by the position assumed by the participant during the reproduction phase (egocentric – 1, egocentric – 2, allocentric – 3, allocentric – 4, and see

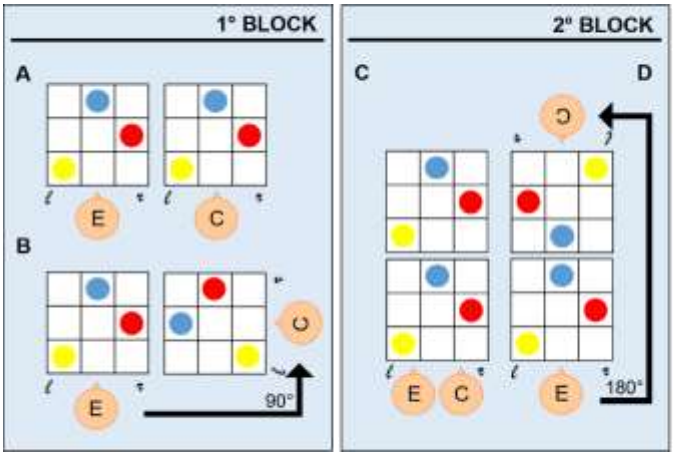

Figure 2.2 Egocentric and allocentric conditions of the visual switching-perspective tasks.
Four conditions are administered to participants in two separate blocks: each block comprises both an egocentric (**A, C**) and an allocentric (**B, D**) condition. In the first block (left panel), the allocentric condition (**B**) results from a 90° rotation respect to the egocentric condition (**A**). In the second block (right panel), the allocentric condition (D) results from a 180° rotation respect to the egocentric condition (C). * E: experimenter; C: child; r: right; l: left

Figure 2.2), and N stands for the number of repetitions per condition (12 trials). Responses were considered correct (trial score = 1) when the participant accurately reproduced the experimenter's configuration during the demonstration phase, despite the spatial position assumed during the reproduction phase and thus despite the confounding visual feedback of the whole scene. For instance, while in the egocentric conditions children can rely on the visual feedback of the scene to copy the layout configuration, in the allocentric conditions they had to mentally rotate the board layout (90 in condition 3, 180 in condition 4) to place the coins correctly according to the configuration presented (see a comparison of conditions 1/2 and 3/4 in Figure 2.2). Therefore, correct responses for the two egocentric conditions (Figures 2.2A,C) were considered as egocentric responses because correct reproduction was based on egocentric coordinates, while correct answers for the two allocentric conditions (Figures 2.2B,D) were considered as allocentric responses because correct reproduction was based on the ability to switch from an egocentric to an allocentric frame of reference. Moreover, we computed a score for “specular” and “casual” responses, given when children positioned coins in a mirror-like configuration concerning the assumed midline and in a way that could not be linked to any of the categories mentioned above, respectively. We evaluated the normal distribution of data applying the Shapiro–Wilk test of normality with the free software R (Free Software Foundation, Boston, MA, United States). Since we verified that data did not follow a normal distribution, we used nonparametric methods for the analysis. Two levels of analysis were performed: an intra-group level, which considered the performance of visually impaired and sighted children to investigate developmental trends separately; an inter-groups level, which compared the performance of visually impaired and participants. Starting from the intra-group level, we conducted four separate mixed permuted ANOVAs with “correct,” “specular,” “egocentric” (only allocentric conditions), and “casual” responses as dependent variables, within-factors “age groups” (three levels: 4–5, 6–7, and 8–9), “coins” (three levels: One, Two, and Three), and “conditions” (four levels: 1, 2, 3, and 4) as independent variables. For the inter-groups level, we performed four separate mixed permuted ANOVAs with “correct,” “specular,” “egocentric” (only allocentric conditions), and “casual” responses as dependent variables, between-factor “subjects” (two levels: Visually Impaired,), and within-factors “age groups” (three levels: 4–5, 6–7, and 8–9), “coins” (three levels: One, Two, and Three), and “conditions” (four levels: 1, 2, 3, and 4) as independent variables. The permuted Bonferroni correction for non-parametric data was applied in case of significant effects to adjust the p-value of multiple comparisons (significant value: $p < 0.05$).

Results

Firstly, we compared the correctness of responses between sighted and visually impaired participants. Figure 2.3 shows that visually impaired (VI) children significantly reported less correct responses than peers, independently of their age group and the difficulty of task

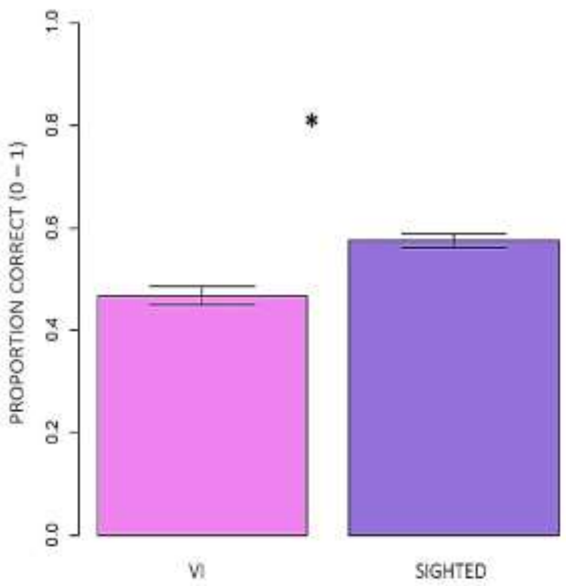

Figure 2.3 Comparison of correctness of responses between visually impaired and sighted participants. The inter-groups analysis shows that visually impaired children perform significantly worse than sighted children (RSS = 5.13, iter = 5000, $p < 2e\text{-}16$; Bonferroni: $p = 0.00$), independently of the age group participants belong to and of the difficulty of conditions.

conditions (inter-groups analysis; main effect: subjects; RSS = 5.13, iter = 5000, $p < 2e–16$; and Bonferroni: $p = 0.00$). The intra-group analysis indicated significant differences between conditions (Figure 2.4). In egocentric conditions (1, 2), correct responses were significantly higher than in allocentric conditions (3, 4) for both sighted (main effect: conditions; RSS = 162.45, iter = 5000, $p < 2e–16$; and Bonferroni: 1 vs. 3 = 1 vs. 4 = 2 vs. 3 = 2 vs. 4: $p = 0.00$), and visually impaired participants (main effect: conditions; RSS = 71.50, iter = 5000, $p < 2e–16$; and Bonferroni: 1 vs. 3 = 1 vs. 4 = 2 vs. 3 = 2 vs. 4: $p = 0.00$). Moreover, the different effect size between sighted and visually impaired children seemed to be related to a development factor (inter-groups analysis; interaction between subjects x age groups; RSS = 0.21, iter = 5000, and $p = 0.0012$). In Figure 2.5, visually impaired participants performed significantly

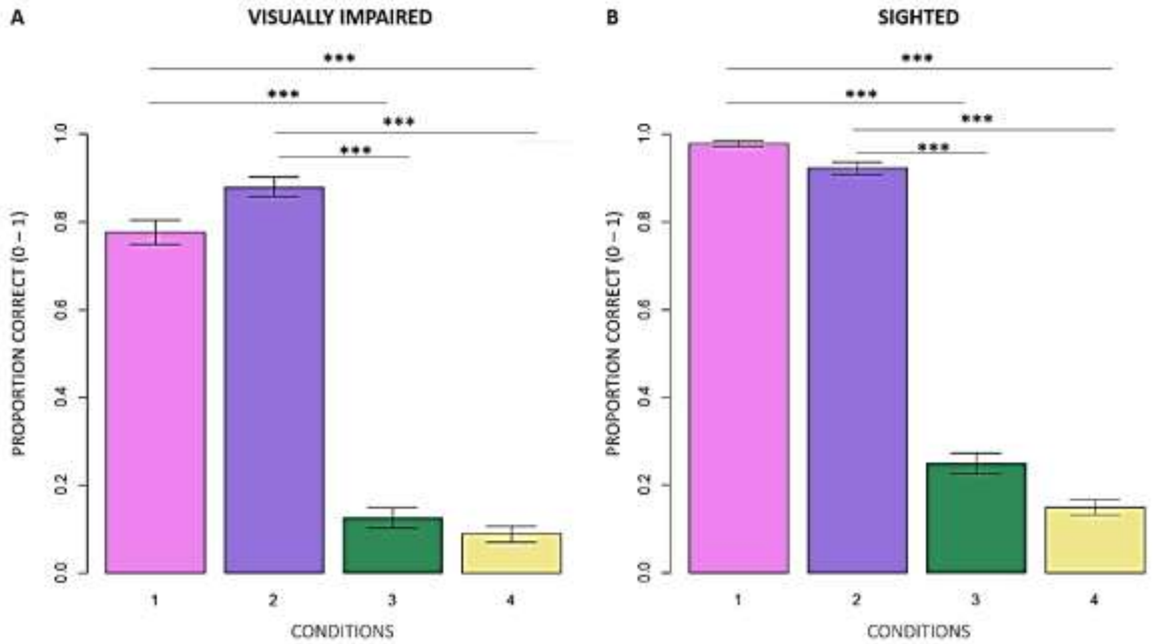

Figure 2.4 Intra-group comparison between conditions.
(A) In egocentric conditions (1, 2), visually impaired participants scor significantly higher in correct responses than in allocentric conditions (3, 4) (RSS = 71.50, iter = 5000, p < 2e-16; Bonferroni: 1 vs. 3 = 1 vs. 4 = 2 vs. 3 = 2 vs. 4 : p = 0.00). **(B)** Sighted participants obtain a similar result in egocentric conditions (RSS = 162.45, iter = 5000, p < 2e-16; Bonferroni: 1 vs. 3 = 1 vs. 4 = 2 vs. 3 = 2 vs. 4 : p = 0.00).

worse compared to typical peers at 4–5 than 6–7 and 8–9 years of age (Bonferroni: 4–5VI vs. 4–5S: p = 0.00; 6–7VI vs. 6–7S: p = 0.06; 8–9VI vs. 8–9S: p = 0.10).

Starting from these findings, a deeper evaluation of accuracy among egocentric conditions revealed a dependency on age groups (Figure 2.6). Indeed, visually impaired children showed a strong developmental trend (interaction between age groups x conditions; RSS = 2.09, iter = 5000, p < 2e–16; and Bonferroni: 4–5_1 vs. 6–7_1: p = 0.00; 4–5_1 vs. 8–9_1: p = 0.00; 6–7_1 vs. 8–9_1: p = 0.00; 4–5_2 vs. 8–9_2: p = 0.00; 6–7_2vs. 8–9_2: p = 0.00), while only 4–5 years old participants showed a similar trend exclusively in condition 2 (interaction between age groups x conditions; RSS = 0.35, iter = 5000, p < 2e–16; and Bonferroni: 4–5_2 vs. 6–7_2: p = 0.00; 4–5_2 vs. 8–9_2: p = 0.00).

To evaluate a possible influence of the experimental condition on correctness, we compared the performance across age groups in terms of correct and specular responses scored by the two experimental groups using confusion matrices (Figure 2.7). The levels of gray indicate whether participants reproduced a configuration ("Reproduced configuration", x-axis)

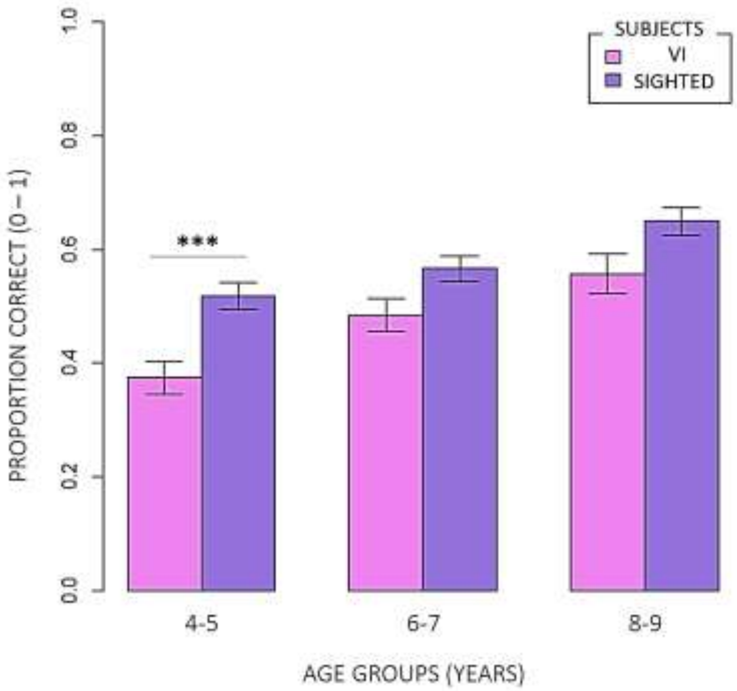

Figure 2.5 Inter-groups comparison between age groups.
Visually impaired participants perform significantly worse compared to sighted peers at 4-5 than 6-7 and 8-9 years of age (RSS = 0.21, iter = 5000, p = 0.0012; Bonferroni: 4-5VI vs. 4-5S: p = 0.00; 6-7VI vs. 6-7S: p = 0.06; 8-9VI vs. 8-9S: p = 0.10).

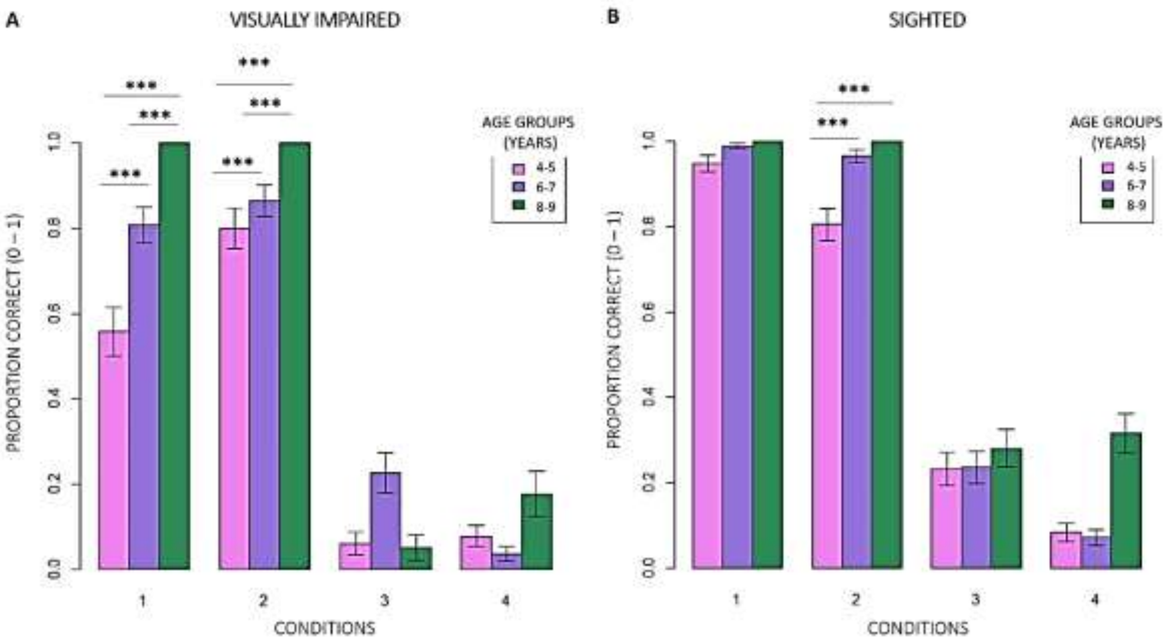

Figure 2.6 Intra-group evaluation of accuracy among egocentric conditions.
(A) Visually impaired children show a strong developmental trend (RSS = 2.09, iter = 5000, p < 2e-16; Bonferroni: 4-5_1 vs. 6-7_1: p = 0.00; 4-5_1 vs. 8-9_1: p = 0.00; 6-7_1 vs. 8-9_1: p = 0.00; 4-5_2 vs. 8-9_2: p = 0.00; 6-7_2vs. 8-9_2: p = 0.00). **(B)** On the contrary, only 4-5 years old sighted participants show a similar trend, and exclusively in condition 2 (interaction between age groups x conditions; RSS = 0.35, iter = 5000, p < 2e-16; Bonferroni: 4-5_2 vs. 6-7_2: p = 0.00; 4-5_2 vs. 8-9_2: p = 0.00).

correctly (dark gray) or specularly (light gray) concerning the experimenter's configuration ("Target configuration", y-axis) in a specific condition. As regards typical children (Figure 2.7B), the number of specular responses resulted higher in allocentric (3, 4) than egocentric (1, 2) conditions, but it gradually reduced with growth. On the contrary, visually impaired participants did not improve their performance across ages, generally relying on allocentric frames of reference (Figure 2.7A). Interestingly, at 4–5 years of age, visually impaired children's specular responses seemed to be higher than peers even in condition 1, where we expected a similar result based on egocentric cues. Figure 2.8 confirms that the tendency to reproduce specular configurations in an egocentric condition (1) was significantly higher in 4–5 years old visually impaired than participants (inter-groups analysis; interaction between subjects x age groups x conditions; RSS = 0.44, iter = 5000, $p < 2e{-}16$; and Bonferroni: 45VI_1 vs. 45S_1: $p = 0.00$). This result suggests a significant developmental delay in the consolidation process of egocentric spatial competencies in the youngest visually impaired children.

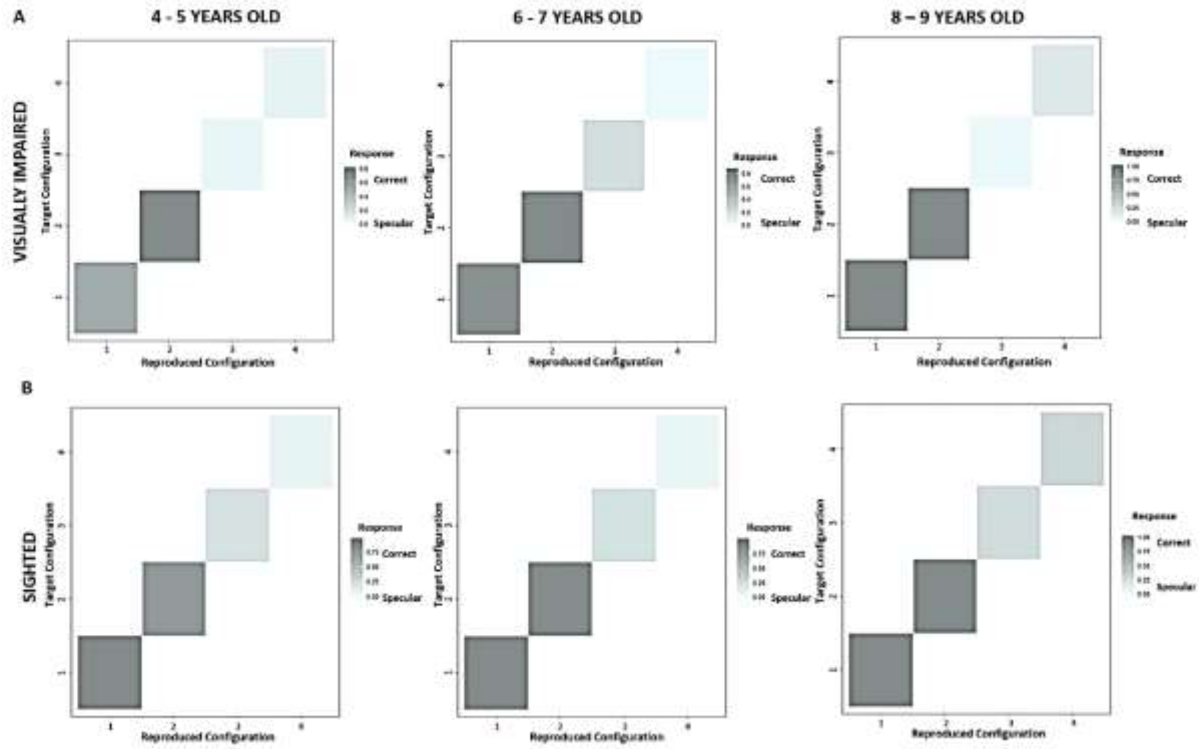

Figure 2.7 Intra-group performance across age groups in terms of correct and specular responses with confusion matrices.
The levels of grey indicate whether participants reproduce a configuration ('Reproduced configuration', x-axis) correctly (dark grey) or specularly (light grey) with respect to the experimenter's configuration ('Real configuration', y-axis) in a certain condition. **(A)** Visually impaired participants do not improve their performance by relying more on allocentric frames of reference, **(B)** while the number of specular responses given by normally sighted children results higher in allocentric (3, 4) than egocentric (1, 2) conditions, gradually reducing with growth.

Overall, our findings suggest that the ability to switch from egocentric to allocentric reference frames depends on the amount of visual experience accumulated during development.

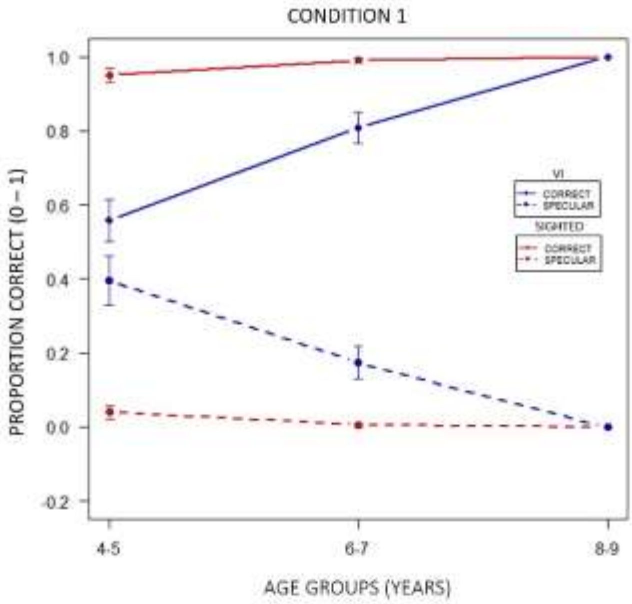

Figure 2.8 Correct and specular responses in egocentric condition 1.
The tendency to reproduce specular configurations is significantly higher in 4-5 years old visually impaired than sighted participants (RSS = 0.44, iter = 5000, $p < 2e\text{-}16$; Bonferroni: 45VI_1 vs. 45S_1: $p = 0.00$). This result might suggest that youngest visually impaired children have a significant developmental delay in the consolidation process of egocentric spatial competencies.

Discussion

Despite the ability to integrate egocentric and allocentric frames of reference that emerges during the first years of life and typically relies on visual experience, to date it is not yet clear when children become able to switch from egocentric to allocentric coordinates and how visual deprivation impacts on this skill. In this work, we tested and verified the hypothesis that children with an atypical visual experience during development (low vision) would show a more substantial reliance on egocentric frames of reference when a mental update of spatial coordinates was required. In particular, we demonstrated that visually impaired children are impaired compared to typical peers in performing a switching-perspective task, requiring them to ignore their egocentric spatial perspective to focus on allocentric cues. Furthermore, visually impaired children showed a dominance of specular responses (i.e., mirror-like representation of space) at 4–5 years of age in configurations that required an egocentric coordinate system.

The first years of life are crucial for the development of executive functions that might play a role in helping children to identify and select the most appropriate spatial strategy according to environmental features (Hermer and Spelke, 1994; Nardini et al., 2008; Vasilyeva and Lourenco, 2012). Since vision is crucial for the maturation of spatial cognition (Foulke, 1982; Thinus-Blanc and Gaunet, 1997), visual impairment can determine delays in the acquisition of spatial planning (Cappagli and Gori, 2016) and spatial updating abilities requiring a switch from egocentric to allocentric coordinates (and vice-versa). In this work, we found that visually impaired children remained anchored to an egocentric representation of space across ages when they were required to rely on allocentric frames of reference to solve the task. Conversely, sighted children improved their performance gradually, showing an increase in the number of correct responses. This result is in line with previous studies that have reported a deficit of visually impaired children in solving tasks based on the mental rotation of the self (Huttenlocher and Presson, 1973; Koustriava and Papadopoulos, 2012; Millar, 1976; Papadopoulos and Koustriava, 2011) or physical objects (Huttenlocher and Presson, 1973; Papadopoulos and Koustriava, 2011; Penrod and Petrosko, 2003). It has recently been hypothesized that the object-centered representation of space cannot be independent of egocentric coordinates (Filimon, 2015). In other words, spatial decisions remained anchored to a purely egocentric spatial reference frame even when spatial locations are referred to external objects. Therefore, it seems that spatial strategies are based on a two-steps process. The first step allows to code space in body-centered coordinates, while the second step allows linking body-centered to objects-centered coordinates. We can speculate that visually impaired children remained anchored to the first step, being able to code space in egocentric coordinates while not rotating mentally body-centered representation according to the spatial layout.

Another interesting result of this work is that visually impaired children manifested a developmental delay in performing the task also from an egocentric point of view. Indeed, at 4-5 years of age they showed more specular than egocentric responses in condition 1 but not in condition 2 (see Figure 2.2A), contrarily to sighted peers that correctly maintained the same perspective (egocentric) in both conditions. In this case, the body midline might play a role in the representation of space based on body coordinates. Previous research in the field has shown that body midline is a reliable reference for spatial judgments when it is spatially aligned with the perceived object (Millar, 1985, 1981), but not when the task requires to cross the body midline to code the spatial properties of the stimulus (Millar and Ittyerah, 1992). Therefore, in the present study we might speculate that condition 2 represents the case in which the body midline is aligned with the spatial configuration of the stimulus, while condition 1 represents the case in which the task requires a body-midline crossing to perceive the stimulus, implying an overall worsen performance. Moreover, it may be assumed that egocentric spatial coding can also be centered on the eye (Rock, 1997). According to this egocentric dichotomy, results obtained in condition 1 might suggest that visually impaired children tend to refer more on their body midline at early ages to encode body midline-crossing space. In contrast, they mainly rely on their visual residual in case of body midline-aligned space.

To conclude, our work suggests that an impoverished visual experience during development negatively impacts on the development of allocentric spatial coding and the acquisition of a correct body-center perspective in case of body midline-crossing targets.

2.3 Haptic-spatial development in blind children

Research on spatial competencies has shown that haptic and visual experience facilitates identifying and localizing objects in the peripersonal space (Postma et al., 2007), defined as space immediately surrounding our bodies (Rizzolatti et al., 1997). Several works have also demonstrated that vision plays a crucial role in developing allocentric spatial coding, e.g., by compensating the egocentric representation of objects location through touch (Newell et al., 2005; Newport et al., 2002; Postma et al., 2007; Spencer et al., 1989). Ungar et al. (1995) and Hollins and Kelley (1988) demonstrated that visually impaired and early-blind adults predominantly based haptic spatial coding of a rotated object configuration on body movements (egocentric cues) instead of external (allocentric) cues. Furthermore, Ruggiero and colleagues (2018) confirmed that congenitally blind adults performed a haptic switching-perspective task worse than blindfolded sighted adults. A study conducted by Pasqualotto and Newell (2007) pointed out that congenitally blind adults performed worse than late blind and blindfolded adults in recognizing the spatial configuration of haptic scenes a static position or after physically assuming a different perspective. These findings confirm that adults with partial (visually impaired) or total (blind) vision loss tend to employ an egocentric spatial strategy to code haptic configurations of stimuli (Spencer et al., 1989; Warren, 1994).

Nonetheless, only a few studies investigated this topic in children with visual disabilities. A recent work by Papadopoulos and Koustriava (2011) suggested that visually impaired children might be impaired in relying on allocentric spatial cues to solve mental rotation tasks, but to date it is still unclear when they become able to utilize properly allocentric cues to perform haptic switching-perspective tasks. Moreover, little is known about how temporary visual deprivation (blindfolding) in sighted children would affect their ability to rely on allocentric coordinates to reproduce a haptic spatial configuration.

In the present study, we employed an experimental paradigm adapted from Martolini et al. (2020), based on the idea that allocentric representation of space emerges from egocentric coordinates. In other words, being able to represent a spatial configuration of stimuli based on external coordinates would require the ability to imagine the same spatial configuration from the perceiver's perspective. Participants were required to perform a switching-perspective task consisting of reproducing a configuration of visual or haptic stimuli by assuming the experimenter's perspective. Contrarily to paradigms aiming at differentiating egocentric and allocentric processes (Burgess et al., 2004; Ruggiero et al., 2018; Wang and Simons, 1999), the task aimed at investigating whether and how children can update spatial coordinates of a scene independently of their current egocentric perspective. In particular, this task allowed us to categorize a type of response (specular response) that we consider as a precursor of allocentric coding, namely when participants provided a spatial configuration that presented both elements of an egocentric and allocentric representation of stimuli. Firstly, we hypothesized that sighted children would encounter more difficulties in performing a switching-perspective task in the haptic modality than in the visual modality. To test this hypothesis, we compared the performance of blindfolded and not-blindfolded sighted children in a haptic and visual switching-perspective task, respectively. Secondly, we hypothesized that the total absence of vision (blindness) during growth would affect the ability to mentally rotate spatial configurations by switching from egocentric towards allocentric haptic landmarks. To test this hypothesis, we assessed whether the ability to shift from egocentric towards allocentric frames of reference is altered in temporary (blindfolding) and total absence of vision (blindness).

Sample

Overall, thirty sighted and ten blind age-matched children between six and thirteen years of age participated in the study. Sighted children were recruited from local schools. Blind children were recruited from a local hospital (IRCCS Mondino Foundation, Pavia, Italy). According to the 'International Statistical Classification of Diseases and Related Health Problems' (ICD-10

(Organization, 1993)), we recruited blind participants with a residual vision from light/sporadic light to no light perception (see Table 2.2 for clinical details of participants). We checked that all blind children reached an adequate level (cut-off ≥ 85) of cognitive development, as assessed with the verbal scale of the 'Wechsler Intelligence Scale for Children' (Wechsler, 2014). Neither of the children reported additional sensory, motor, or neurological disabilities. Concerning sighted participants, fifteen children (mean age: 9.20 ± 0.12 years) performed the task in the haptic modality, while fifteen age-matched peers performed the visual version of the same task. To verify whether the absence of vision has an impact on the ability to switch from egocentric to allocentric frames of reference, we compared the performance of the blind children (mean age: 8.90 ± 0.05 years) with a selected group of age-matched sighted peers. The local Ethical Committee approved the study, and participants' parents were asked to sign written informed consent under the Declaration of Helsinki. The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.62 (Partial eta squared $\eta^2_p = 0.72$; see Ruotolo et al., 2015);
- α err. prob. = 0.05;
- power (1-β err. prob.) = 0.95.

Task and procedure

Participants performed a switching-perspective task to assess the ability of participants to change their spatial perspective to reproduce a configuration of visual or haptic stimuli. Stimuli consisted of three textured (haptic task) or colored (visual task) coins positioned on a plastic board realized as a 30x30 cm grid of white Velcro straight vertical and horizontal lines. When the task was administered in the visual modality, high-contrast colored coins (bright red, blue, and yellow) were used, while when the task was administered in the haptic modality, coins with different textures (rough, soft, wrinkled) were used, and sighted participants were blindfolded. In both modalities, the task comprised two consecutive phases: 1) the experimenter presented a configuration of coins on his/her own board by allowing the participant to visually or haptically explore it (demonstration phase); 2) the participant was asked to reproduce on his/her board the configuration presented (reproduction phase). The physical spatial position of the participant was defined based on four possible reproduction conditions. Two conditions implied an egocentric perspective in the sense that the spatial perspective of the experimenter showing the configuration to be reproduced and the spatial perspective of the participants asked to reproduce it coincided. Conversely, the other two conditions implied an allocentric perspective because the participant was asked to physically rotate his/her position in space with respect to the experimenter. Figure 2.9 depicts the four reproduction conditions: 1) egocentric condition, with the participant sitting next to the experimenter and the two boards next to each other; 2) egocentric condition, with the participant sitting next to the experimenter and the boards position and the boards next to each other, in front of them; 4) allocentric condition, with the participant sitting rotated 180 degrees to the experimenter position and one board above the other, in front of them. The rationale behind the two egocentrics (one board adjacent to each other and one board above each other) and allocentric (90° rotation and 180° rotation) conditions is to provide two different spatial arrangements (left-right and up-down) to test the egocentric and allocentric perspective, sitting rotated 180 degrees to the experimenter position and one board above the other, in front of them. The rationale behind the two egocentrics (one board adjacent to each other and one board above each other) and allocentric (90° rotation and 180° rotation) conditions is to provide two different spatial arrangements (left-right and up-down) to test the egocentric and allocentric perspective, assuming that left-right (for egocentric) and 90° rotation (for allocentric) are easier compared to up-down (for egocentric) and 180° rotation (for allocentric) conditions. For each participant, the testing session was divided into two blocks, comprising one egocentric and one allocentric condition to randomize participants' spatial positions. At the beginning of each block, the participant's physical spatial position was defined according to the four possible conditions illustrated in Figure 2.9. At the beginning of each trial in each experimental block, the participant familiarized with the setup in a short practice session of a few configurations to test the task's comprehension. The difficulty per condition increased along with the number of coins used by the experimenter: 1) simple level, with one coin; 2) intermediate level, with two coins; 3) hard level, with three coins. For each level, four configurations were presented to the participant in random order. During the demonstration and the reproduction phases, participants were allowed to explore the visual (sighted participants) or haptic (blind and blindfolded sighted participants) spatial configuration on the experimenter's board. We allowed children to look at and touch the model configuration on the experimenter's board to avoid the interference of memory delays between the encoding and the reproduction phases (Gaunet and Rossetti, 2006). Children performed a total amount of 48 trials (12 trials per condition) on the same day in about one hour, with short breaks at any time during the

Participant	Age range	Pathology	Residual Vision
#1	6-9	Bilateral microphthalmia and severe anterior segment dysgenesis	No light perception
#2	11-13	Leber congenital amaurosis	Sporadic light perception
#3	6-9	Leber congenital amaurosis	Light perception
#4	6-9	Leber congenital amaurosis	Light perception
#5	11-13	Norrie disease	No light perception
#6	6-9	Leber congenital amaurosis	Light perception
#7	11-13	Leber congenital amaurosis	Light perception
#8	6-9	Leber congenital amaurosis	Light perception
#9	6-9	Leber congenital amaurosis	Sporadic light perception
#10	6-9	Peters' anomaly, microphthalmia	No light perception

TABLE 2.2 Clinical details of blind participants (N = 10).
The table shows the age range at test, the pathology, and residual vision at a distance of 3 m of blind participants.

experimental session.

Data analysis and statistics

We evaluated sighted and blind children's ability to correctly reproduce spatial configurations of coins on a board by relying on visual (only sighted children) or haptic (sighted and blind children) feedback, independently of the spatial perspective assumed during the experiment. More specifically, we compared the performance of sighted and blindfolded sighted participants in the reproduction of visual and haptic configurations (first step), then we compared the performance of blindfolded sighted and blind participants in the reproduction of haptic configurations (second step). We defined four categories of the response given after a visual or haptic exploration of the configuration presented by the experimenter: 1) correct response, when the participant accurately reproduced the configuration; 2) specular response, when the participant reproduced a mirror-like configuration with respect to the assumed midline; 3) egocentric response, when the participant merely copied the configuration despite the condition of reproduction; 4) casual response, when the participant reproduced a configuration that was not linked to any of the categories previously mentioned. We calculated a score (maximum trial score = 1) for each of the four response categories in all the four conditions, defined by the spatial position assumed by participants during the demonstration and reproduction phases (egocentric - 1, egocentric - 2, allocentric - 3, allocentric – 4), as follows:

$$S = \frac{\sum_{i=1}^{N} nr}{N}, \tag{1}$$

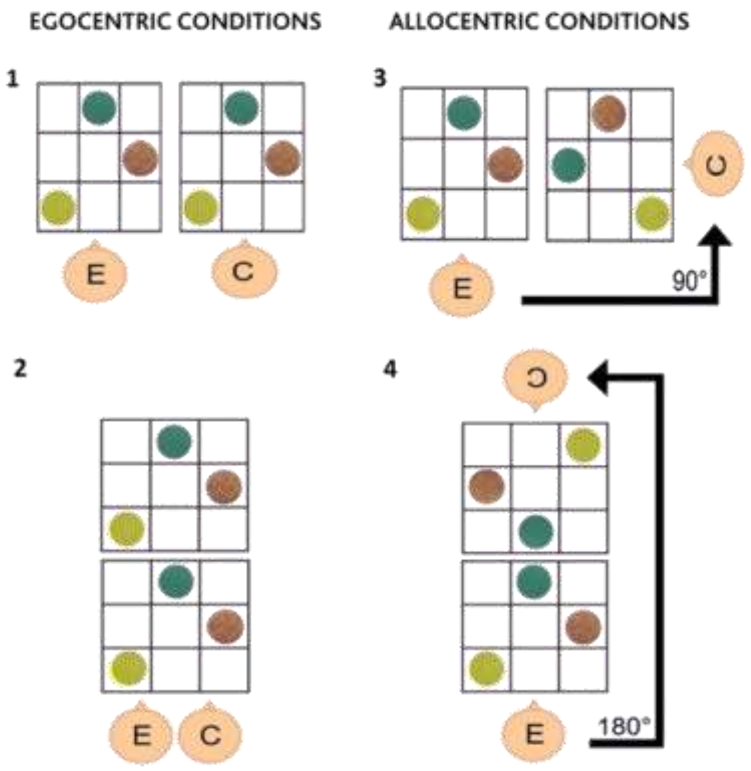

Figure 2.9 Conditions of the visual and haptic switching-perspective task.
The experimenter (E) shows to the child (C) a configuration of coins on a plastic board to be explored in a visual or haptic modality. Then the child is asked to reproduce the same configuration on his own plastic board in front of him. Each condition refers to a specific reference frame: conditions 1) and 2) are solved with an egocentric frame of reference, while conditions 3) and 4) expect an allocentric frame of reference to be reproduced correctly.

where *S* stands for "Score”, *nr* stands for the number of responses, and *N* stands for the number of repetitions per condition (12 trials). For instance, we considered correct all responses where children relied exactly on reproduced the experimenter's configuration. Therefore, to produce a correct response in the egocentric conditions, they had to copy the experimenter's configuration. To reproduce a correct response in the allocentric conditions, they had to mentally rotate the experimenter's board of 90° and 180° in conditions 3 and 4, respectively. We verified that data did not follow a normal distribution by applying the Shapiro-Wilk test of normality with the free software R (Free Software Foundation, Boston, MA, USA).

The first level of analysis evaluated whether the use of different sensory modalities (vision and touch) affects the ability of sighted children to switch from egocentric to allocentric frames of reference along with childhood (inter-modality level). We conducted a mixed permuted ANOVA with *correct responses* as a dependent variable, between-factor "*modality*" (two levels: visual, haptic), and within-factor "*conditions*" (four levels: 1, 2, 3, 4). The second level of analysis compared the performance of blind and sighted children in the haptic modality to evaluate whether the complete absence of vision affects the development of switching-perspective abilities (intra-modality level). We analyzed the difference in correct responses scored by blind and sighted participants with a mixed permuted ANOVA with *correct responses* as a dependent variable, between factor "*subjects*" (two levels: Blind, Sighted), and within-factor "*conditions*" (four levels: 1, 2, 3, 4). For both levels of analysis, the permuted Bonferroni correction for non-parametric data was applied in case of significant effects to adjust the p-value of multiple comparisons (significant value: $\alpha = .05$).

Results

We evaluated whether the use of different sensory modalities (vision and touch) affects sighted children's performance to switch from a body-centered to an object-centered perspective (inter-modality level). As shown in Figure 2.10A, the proportion of correct responses in the haptic version of the switching-perspective task was significantly lower thanin the visual version of the same task, regardless of the reproduction condition (main effect: modality; RSS = 2.45, iter = 5000, $p < 2e\text{-}16$; t = -3.20, $p = 0.0014$), suggesting that sighted children have worse spatial performance in the haptic modality. Figure 2.10B showed that the performance in the haptic and visual versions of the task is dependent on the experimental conditions (interaction between modality x conditions; RSS = 2.46, iter = 5000, $p < 2e\text{-}16$). Children enrolled in the haptic task performed worse compared to children enrolled in the visual task in the first egocentric condition (Bonferroni: haptic_1 vs. visual_1: $p = 0.003$; haptic_2 vs. visual_2: $p = 0.27$) and in both allocentric conditions (3, 4) (Bonferroni: visual_3 vs. haptic_3: $p = 9.51e-08$; visual_4 vs. haptic_4: $p = 4.81e-08$). Since vision might help build a spatial representation of the setup while touch might be a body-related sense, we evaluated the proportion of egocentric responses in the allocentric conditions (incorrect responses) of sighted participants. The results are shown in Figure 2.11 and confirmed that children

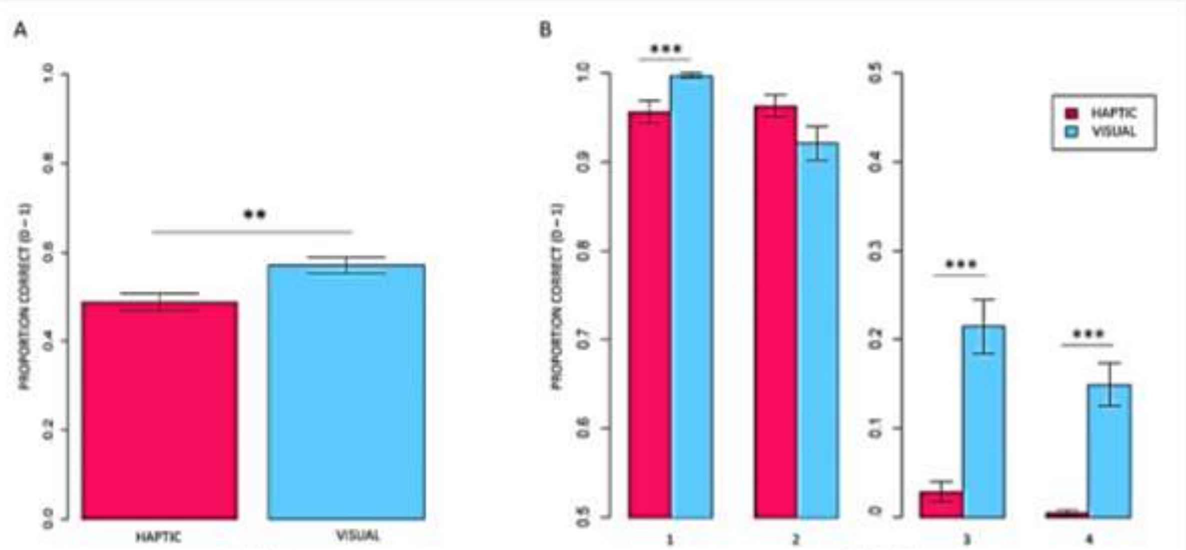

Figure 2.10 Comparison of correctness between sighted and blindfolded sighted children in the visual and haptic domain.
A) Participants show a worse performance in the haptic than in the visual domain, independently of the reproduction condition ($p < 0.01$). **B)** In the haptic task the proportion of correct responses is lower than in the visual task in the first egocentric condition ($p < 0.01$) and in both allocentric conditions (3, 4) ($p < 0.0001$).

performed more egocentrically in the haptic than in the visual version of the task, independently of the spatial position assumed (permuted unpaired two-tailed t-test; haptic_3 vs. visual_3: $t = 3.78$, $p < 0.0001$; haptic_4 vs. visual_4: $t = 7.81$, $p < 0.0001$). Moreover, in the first egocentric condition, the proportion of casual responses (between 0 and 1) was higher in the haptic compared to the task's visual condition (permuted unpaired two-tailed t-test; haptic vs. visual: $t = 2.83$, $p = 0.002$). This finding might be related to children's difficulty in encoding space in the absence of visual feedback. To understand whether total visual deprivation from birth influences switching-perspective competencies in the haptic domain, we compared the ability to use haptic egocentric and allocentric frames of reference appropriately in blind and sighted children (intra-modality level). Interestingly, Figure 2.12A showed that correct responses of blind and sighted participants were similar (main effect: subjects; RSS = 0.13, iter = 493, p =

0.17). As for the inter-modality analysis, the performance of the two experimental groups differed among conditions (interaction between subjects x conditions; RSS = 1.00, iter = 5000, $p < 2e-16$), as explained in Figure 2.12B. Blind participants performed worse than sighted peers in condition 1 (egocentric) (Bonferroni: blind vs. sighted: $p < 0.0001$), while they performed better than sighted peers in condition 4 (allocentric) (Bonferroni: blind vs. sighted: $p = 0.043$).

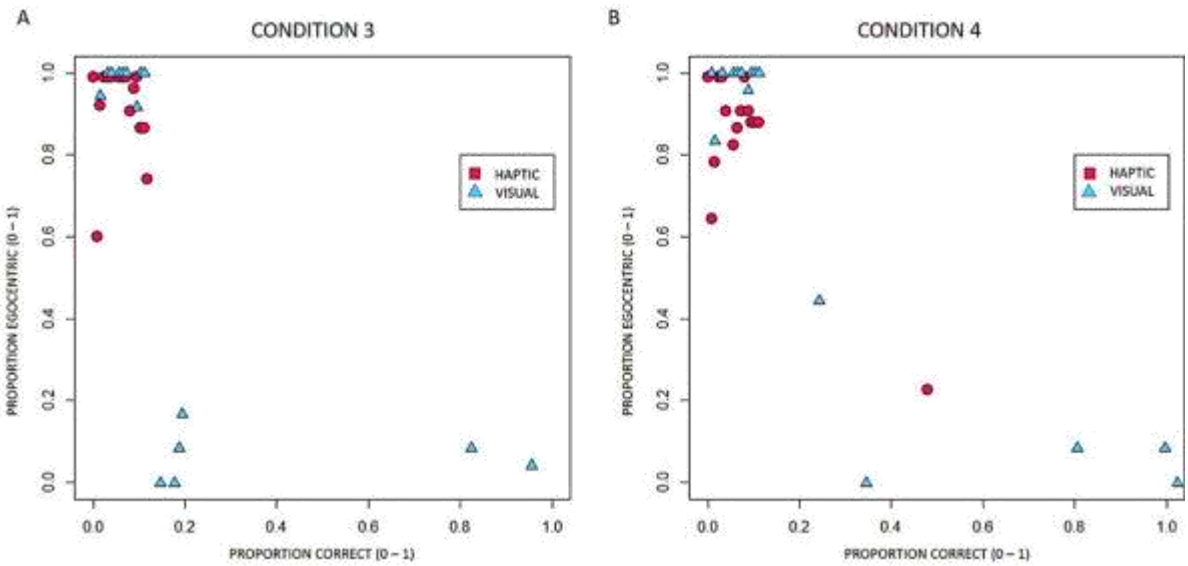

Figure 2.11 Proportion of egocentric responses in the allocentric conditions (3, 4) by sighted children in the visual and haptic domain.
A) Sighted children perform more egocentrically in the haptic (while blindfolded) than in the visual modality in both condition 3 ($p < 0.0001$) **B)** and 4 ($p < 0.0001$).

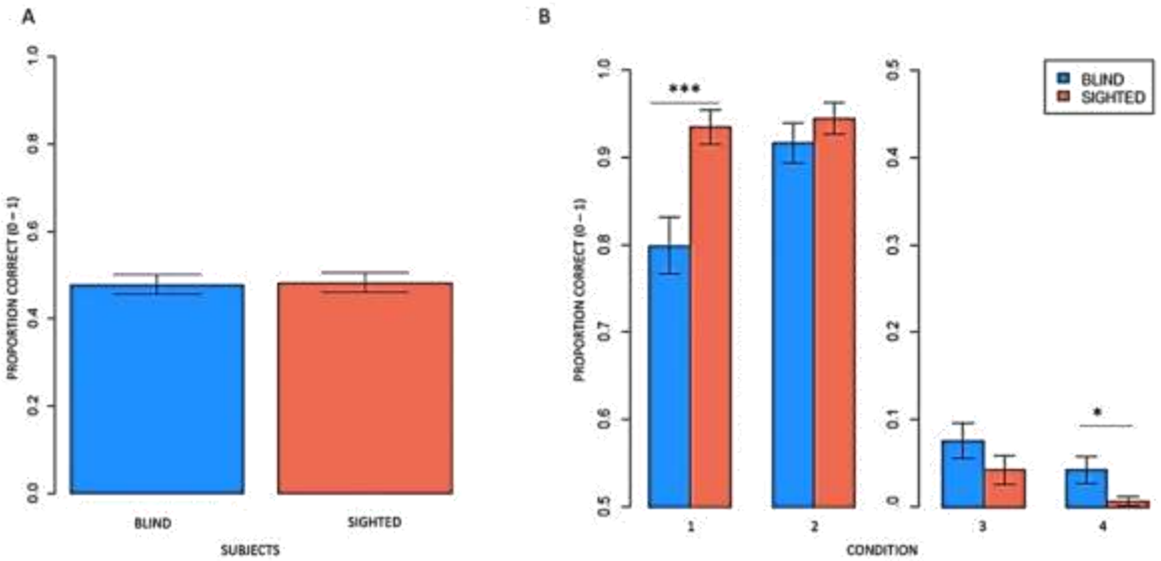

Figure 2.12 Comparison of correctness between blind and blindfolded sighted children in the haptic domain.
A) The proportion of correct responses scored by blind participants are similar to blindfolded sighted peers ($p = 0.17$). **B)** In the first egocentric condition, blind participants perform worse than sighted peers ($p < 0.0001$). On the contrary, blind children perform better than sighted participants in the fourth allocentric condition ($p < 0.05$).

More specifically, in condition 4 (allocentric, Figure 2.13), a significantly higher proportion of egocentric responses was obtained by sighted participants (permuted unpaired two-tailed t-test; blind vs. sighted: t = -4.72, $p < 0.0001$). These results indicate that children with a normal visual experience are more impaired than totally visually deprived peers when asked to reproduce a configuration from a different spatial position. Moreover, in condition 1 (egocentric), the proportion of specular responses (between 0 and 1) significantly increased for blind children (permuted unpaired two-tailed t-test; blind vs. sighted: t = 3.89, $p < 0.0001$). This result suggests that there might be a significant delay in the developmental process of egocentric spatial competencies in blind children. To sum up, results indicated that the temporary absence of vision might impair allocentric spatial abilities in sighted children only to use haptic cues. Simultaneously, a total visual deprivation from birth might compromise the development of egocentric more than allocentric frames of reference in the haptic modality.

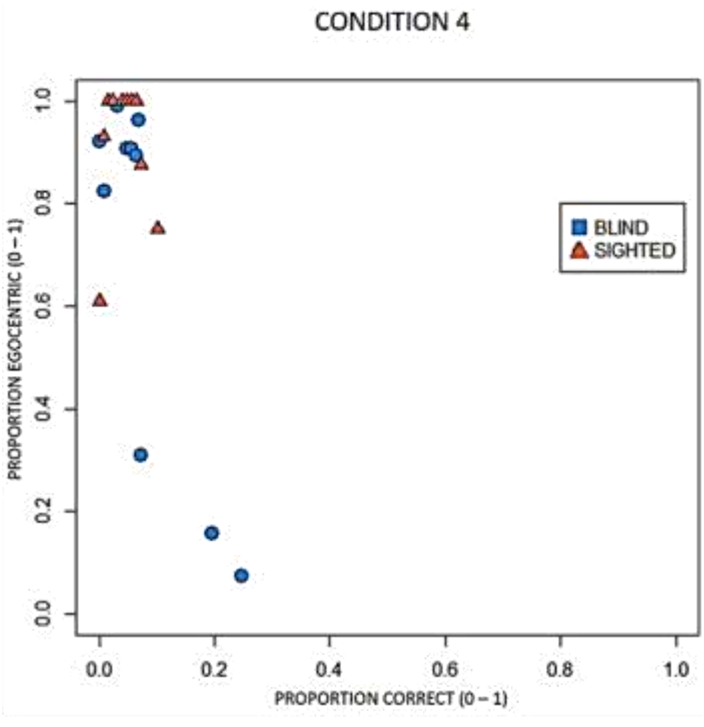

Figure 2.13 Proportion of egocentric responses in allocentric condition 4 by blind and blindfolded sighted children in the haptic domain.
Sighted participants scor a higher number of egocentric responses than blind peers when positioned 180° rotated to the experimenter's position ($p < 0.0001$).

Discussion

In this work, we hypothesized that temporary visual deprivation (blindfolded sighted children) and permanent and total visual deprivation (congenital blind children) would negatively impact the ability to perform a switching perspective task in the haptic domain. To test these hypotheses, we evaluated participants' ability to reproduce a spatial configuration of stimuli by ignoring their current egocentric perspective and by mentally assuming the experimenter’s egocentric perspective.

Results confirmed our first hypothesis, showing that sighted children tend to rely more on allocentric cues when visual feedback is present (visual condition of the task) while their egocentric perspective dominates spatial representation of stimuli when only haptic feedback is present (haptic condition of the task). This finding confirms previous works on sighted adults reporting the prevalence of an object-centered representation of space in the haptic modality (Kappers, 1999; Kappers and Koenderink, 1999; Klatzky, 1999). Indeed, a study conducted by Newport and colleagues (2002) showed that visual cues, even when non-informative, significantly increased sighted adults' performance in orienting a bar correctly, while blindfolding significantly decreases their performance. Therefore, haptic spatial representation seems to rely mainly on egocentric landmarks, while visual coding provides an environment- and object-centered perspective. Moreover, it has been demonstrated that mental manipulation of space is enhanced by assuming allocentric frames of reference, as in the visual domain, while the haptic modality is based on body movements that are considered mainly egocentric (Milner and Goodale, 1995). Surprisingly, the results did not confirm our second hypothesis. Indeed, blind children correctly performed the haptic task's allocentric conditions and provided more correct responses compared to sighted peers, indicating that the ability to shift from egocentric to allocentric coordinates is preserved despite blindness. This result seems in contrast with previous studies showing the predominant use of an egocentric frame of reference by blind individuals in haptic mental rotation tasks (Giudice, 2018; Millar, 1994; Schinazi et al., 2016; Ungar et al., 1995).

Conversely, a similar finding resulted from a study by Postma and colleagues (2007) comparing the performance of blind and blindfolded sighted adults in the haptic processing of objects on a board before and after a physical rotation. They found out that blind participants performed better than blindfolded adults when they referred to other objects on the board and not to the board itself to encode spatial information. The authors called the ability of blind individuals to represent peripersonal space as a route “allocentric intrinsic spatial coding” (Brambring, 1982), different from assuming the surrounding frame as a reference (allocentric extrinsic spatial coding; see Ungar et al., 1995). A possible explanation of our result is that allocentric intrinsic haptic skills in peripersonal space develop during childhood and consolidate adulthood. Interestingly, we found out that blind children were more impaired than blindfolded sighted peers in reproducing the task egocentrically (condition 1), showing a higher proportion of specular responses, independently of the age. The same result was found in our recent paper, where low vision children reproduced more specular than egocentric configurations when a body-centered perspective was required to solve a visual switching-perspective task (Martolini et al., 2020b). This result might be related to the role of body midline in egocentric spatial representation. Since egocentric spatial coding has been also considered centered on the eye (Rock, 1997), we might assume that a visual impairment centers the body-centered frame of reference on the body midline, regardless of the spatial position of objects. Moreover, the reliability of the body midline assumed as reference point has been demonstrated in case of aligned objects (Millar, 1985, 1981) but not in body midline-crossing spatial tasks (Millar and Ittyerah, 1992). Consequently, blind children might be impaired in tasks requiring body midline crossing to solve spatial configurations.

To conclude, this study suggests that vision plays a fundamental role in representing space based on allocentric frame of reference, while haptic spatial coding skills remain anchored to egocentric frame of reference for sighted children with temporary visual deprivation. On the contrary, blind children with a total absence of visual feedback might enhance their haptic spatial representation using allocentric intrinsic frames of reference. At the same time, they seem to be impaired in developing an egocentric perspective in the case of body midline-crossing targets.

2.4 Auditory space in adults with temporary visual deprivation

Vision constitutes the most important sensory input to comprehend the spatial properties of the world (Thinus-Blanc and Gaunet, 1997) and shape discrimination is considered one of the most peculiar visual features of objects (Erdogan and Jacobs, 2017; Milner, 1974; Peelen et al., 2014; Pietrini et al., 2004). Since it has been shown that visual deprivation affects the processing of spatial information, it would be interesting to investigate whether and how temporary visual deprivation impacts the ability to perceive the shape of an object conveyed with alternative modalities such as audition. Some recent studies have explored the role of audition in complementing or substituting for vision in shape perception, showing that both sighted and visually impaired individuals can use hearing to process shape information when vision is impoverished or absent (Bizley and Cohen, 2013; Carello et al., 1998). For instance, it has been shown that audition alone can provide useful information about shape curvature (Boyer et al., 2015) and that friction sounds produced when drawing are sufficiently informative to evoke the underlying gesture and recognize the drawn shapes (Thoret et al., 2014). To date, it is not clear whether auditory shape recognition is influenced by the same factors that affect visual shape recognition, such as the property of contours closure. According to the Gestalt principle of 'closure' (Wertheimer, 1923), the most relevant cue that allows us to perceive an object is its closed contour, which makes a shape global and, consequently, segregates the object from its background.

In the present study, we investigated whether such visual perception properties, e.g., closeness, are automatically transferred to audition (see Martolini et al., 2020). Therefore, we hypothesized that auditory shapes with closed contours would be discriminated better than with auditory shapes with open contours. To test this hypothesis, we proposed an auditory shape recognition task where blindfolded sighted adults were asked to identify four shapes using the sound conveyed through a set of consecutive loudspeakers embedded on a fixed two-dimensional vertical array.

Sample

Twenty-two sighted volunteers participated in the study and were divided into two groups. Eleven adults (age range: 19–38 years, mean age: 26.9 ± 6.36 years, seven females) were assigned to the first group, while 11 adults (age range: 20–29 years, mean age: 24.5 ± 2.73 years, six females) were assigned to the second group. All participants were recruited from a list of volunteers at the Italian Institute of Technology (Genoa, Italy) and monetary compensation was provided for their participation. None of the participants reported visual or auditory impairments, musculoskeletal or neurological pathologies. All participants gave written consent to the experimental protocol, as required by the Declaration of Helsinki and the local Ethics Committee (Comitato Etico ASL3 Genovese). The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.25 (Cohen's d = 1.30; see Carello et al., 1998);

- α err. prob. = 0.05;
- power (1-β err. prob.) = 0.95.

Task and procedure

Participants entered the room blindfolded to avoid seeing the setup. The whole experiment was performed on the same day in about 30 min. Before starting the experimental session, all participants were familiarized with a tactile version of the four shapes (diamond, house, staircase, spiral) presented in the auditory shape recognition task (Figure 2.14A). The shapes were 2D paper figures, whose orientation and dimension matched those of the auditory shapes in the recognition task. Specifically, blindfolded participants were asked to recognize tactile figures in a fixed position on a table in front of them by following the contours with one or both hands. It was not permitted to manipulate figures by handling them. The tactile recognition task was not performed before the post-training session. The auditory shape recognition task required participants to formally recognize four semantic shapes (diamond, house, staircase, spiral) presented as continuous sounds. The experimental setup used to present auditory shapes consisted of 25 loudspeakers embedded in a fixed array resulting in a 5 rows × 5 columns

auditory matrix (Figure 2.14B). Each loudspeaker was positioned at the center of a 5 cm × 5 cm box, and the distance between two consecutive speakers was 5.5 cm. Stimuli consisted of auditory shapes resulting from adjacent loudspeakers' consecutive activation, where the second speaker of the second row of the auditory matrix was always activated first. Auditory shapes

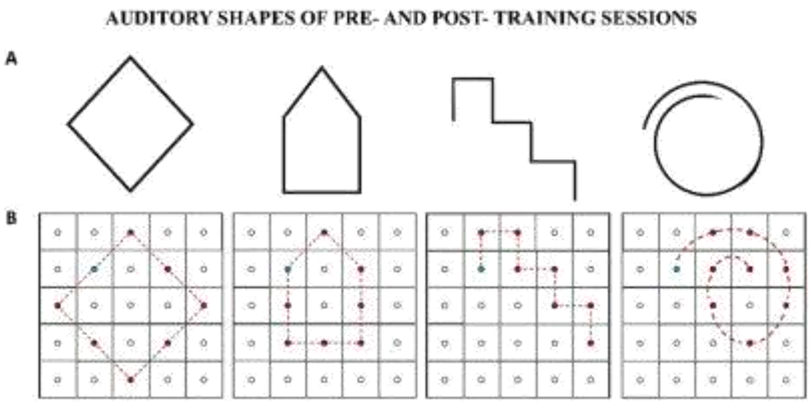

Figure 2.14 Materials and methods of the auditory shape recognition task.
(A) Before starting the experiment, all participants are familiarized with tactile versions of the four shapes (diamond, house, staircase, spiral), included in the auditory shape recognition task. The dimensions of the tactile and the auditory shapes are matched (thickness 1 cm). **(B)** The auditory shape recognition task requires participants to recognize the four shapes presented auditorily by the consecutive activation of adjacent loudspeakers embedded in a 25 × 25 cm matrix. The dots indicate the auditory stimuli that compose the auditory shapes (blue dots indicate the starting sounds).

were designed to have the same duration (9 s from activating the first loudspeaker to turning off the last loudspeaker) to avoid the risk that participants could recognize the shapes by relying not on the spatial occurrence of sounds but on their duration. The auditory stimuli were generated by readapting the procedure used in the work by Vercillo et al. (2017). Since displacements in space and durations were fixed at 44 cm and 9 s, respectively, the velocity of migration was maintained constant across the experiment. The sound was a white noise burst at 500 Hz, generated with the software TrueRTA™ (True Audio®, Andersonville, TN, USA). A laptop controlled the speakers *via* MATLAB (R2010a, The MathWorks, USA). The task required participants to sit at a distance of about 40 cm from the array of loudspeakers with the experimenter sat next to the participant to monitor the head's position, and the height of the chair was adjusted to have the central speaker at eye level. After familiarizing the tactile versions of the shapes, participants performed a practice session where two auditory shapes were reproduced, without any feedback from the experimenter, to realize the kind of sounds they had to listen. At the end of the practice session, the experiment started with participants asked to listen to the auditory shapes presented in pseudo-randomized order and to name verbally the shape perceived. Each participant performed 40 experimental trials (10 trials per shape) and short breaks were allowed at any time during the session.

Data analysis and statistics

For each participant, we calculated an index of correctness given as the number of correct responses for each auditory shape divided by the total number of trials for each shape (e.g., five correct responses for the diamond gave an index of the correctness of 0.5). We verified that data were normally distributed, performing the Shapiro–Wilk test of normality using the free software R (Free Software Foundation, Boston, MA, USA). We conducted a one-way ANOVA with ‘recognition score’ (index of correctness) as the dependent variable and ‘shapes contours’ as within-factor (two levels: Open, Closed).

Results

Figure 2.15 represents the performance of all participants collapsed in a single group. Indeed, no significant difference was observed between the two groups in recognizing auditory shapes ($F_{(1, 20)} = 0.29$, $p = 0.59$). We calculated that participants' capabilities in recognition of auditory shapes were around the chance level (recognition score around 0.25). This poor ability might be related to sighted people's difficulty to recognize shapes through audition instead of vision. Results showed that the recognition score was significantly higher with open- than closed-contour shapes ($F_{(1, 20)} = 7.24$, $p = 0.014$). This finding indicates that auditory open shapes were perceived better than auditory closed shapes by blindfolded sighted participants.

Moreover, we calculated an index of error (inverse of the correctness index) by considering the two groups separated. Such index was computed as the number of times out of all trials where participants named the wrong shapes (e.g. naming, shell or stairs or house when presented with diamond). In this way, confusing the auditory shape presented (e.g. diamond) with one of the other three (e.g. house, shell, stairs) was considered an error. Significant results were obtained only for the first group of participants with the diamond (closed shape) and the shell (open shape). When presented with diamond, the index of error for the house (closed shape) was significantly higher than the stairs (open shape) ($t_{10} = 3.24$; $p = 0.0089$). For the shell, the index of error was significantly higher with respect to the stairs ($t_{10} = 2.51$; $p = 0.031$). This result provided evidence that participants did not confuse closed and open shapes,

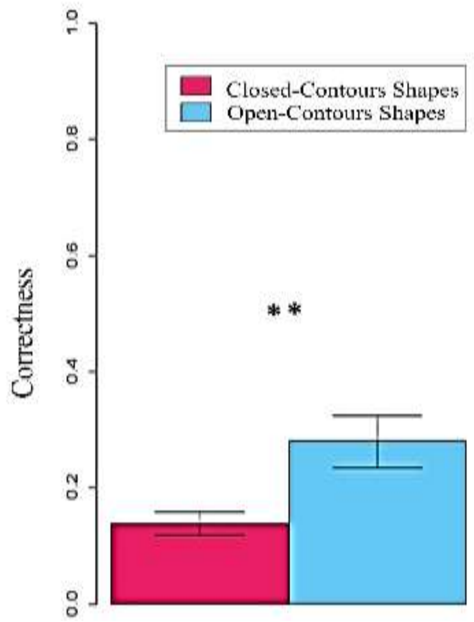

Figure 2.15 Performance of participants in the auditory shape recognition task.
Participants perceived open-contour shapes more correctly compared to closed-contour shapes, independently of the group they belong to ($p < 0.01$).

suggesting that an object's visual properties as shape closeness, can also be considered an auditory property.

Overall, our findings demonstrated that contrarily to our hypothesis, shapes with open contours conveyed through sounds are discriminated better than auditory shapes with closed contours.

Discussion

Recent studies have demonstrated that audition can effectively convey spatial information when complementing and substituting visual input, which is the most predominant sense for spatial perception (Bizley and Cohen, 2013; Carello et al., 1998). In the present work, we hypothesized that the closeness of contours would have a key role in the discrimination of shapes conveyed through sounds. To verify such hypothesis, we evaluated blindfolded sighted adults' performance in an auditory shapes recognition task, asking them to discriminate two shapes with closed contours and two shapes with open contours by listening to continuous sounds in front of them.

Contrarily to our hypothesis, results indicated that open-contour shapes were perceived better than closed-contour shapes in the auditory domain. Although we might suppose that discriminating shapes with similar features (e.g., diamond and house) would be harder than with more pronounced differences (e.g., diamond and stairs), a possible explanation is that closed-contour shapes are more typical in the visual domain. Therefore hearing might not be the most accurate and precise modality to process such stimuli. For instance, it has been reported that the detection of two-dimensional visual shapes is more rapid for closed- than open-contour stimuli (Elder and Zucker, 1993) and that visual closed-contour shapes are processed in a faster and precise way compared to shapes conveyed with non-visual senses (Garrigan, 2012). Furthermore, it might be possible that closure property is less predominant in auditory shape recognition compared to visual shape recognition. According to this statement, a study by Gori and colleagues (2017) reported that perception and reproduction of sonorous closed geometrical shapes failed in early-blind individuals, while other studies indicated that blind people have superior processing of open shapes in the form of linear audio motion (Lewald, 2007).

Therefore, our result indicates that the ability to perceive auditory shapes with closed-contour is altered by temporary visual deprivation.

2.5 General conclusions

Empirical evidence suggests that the ability to process spatial information based on allocentric cues is promoted by visual experience (Pasqualotto et al., 2013; Thinus-Blanc and Gaunet, 1997) and that auditory and haptic spatial representation are calibrated by vision across development (Gori et al., 2012b). Nonetheless, several aspects related to spatial development are still unknown and the studies presented in Chapter 2 aimed to further investigate this topic.

The first study presented in Section 2.2 aimed at clarifying the effect of partial loss of vision (low vision) on the development of visual egocentric and allocentric frames of reference. Indeed, it has been demonstrated that visual experience has a pivotal role in spatial development, but no study to date investigated whether an impoverished visual experience compromises the ability to switch from egocentric to allocentric spatial coordinates during childhood (namely low vision). This study indicates that partial but permanent loss of vision affects the development of switching perspective abilities, with possible negative outcomes on overall spatial competence. Moreover, this study suggests that low vision children tend to remain anchored to a mixed (specular) perspective that results from the combination of egocentric and allocentric cues, possibly suggesting the key to understand the cause of the spatial developmental delay observed in this and other studies in the literature.

The second study presented in Section 2.3 investigated the impact of a total loss of vision (blindness) on the development and integration of haptic egocentric and allocentric frames of reference. Indeed, it has been shown that adults with blindness predominantly code space through touch, but only a few studies investigated this topic in children with visual disability. Research indicates that visually impaired children are impaired in spatial tasks requiring allocentric spatial coding, but no study to date investigated whether and how they become able to update spatial coordinates of a scene independently of their current egocentric perspective. This study shows that total loss of vision does not impair children's ability to develop a coherent haptic spatial representation based on allocentric spatial cues. Taken together, the results of the first and the second studies indicate that while the visual experience is necessary for the development of allocentric spatial coding in the visual domain, it is not necessary to develop the ability to switch from egocentric to allocentric coordinates in the haptic domain. Such results suggest that mechanisms other than visual experience might support haptic spatial development, e.g. body midline could drive the consolidation of egocentric-allocentric switching perspective abilities in children with the absence of visual feedback from birth.

The third study is presented in Section 2.4 and aimed at assessing the role of audition in conveying spatial information when visual feedback is absent. Indeed, several pieces of evidence indicate that spatial properties typically conveyed with vision (e.g. shape) can be successfully conveyed also with audition, but no study to date explored whether auditory perception is influenced by the same factors that influence visual perception (e.g. contours of shape). In the present work, we hypothesized that the closeness of contours would have a key role in the discrimination of shapes conveyed through sounds. This study's results indicate open-contour shapes were perceived better than closed-contour shapes in the auditory domain, while the opposite pattern is documented in the visual domain. Moreover, findings show that the ability to perceive auditory shapes with closed-contour is altered by temporary visual deprivation, further confirming the predominant role of vision on spatial perception.

Future works may focuse the attention on the performance of sighted compared to visually impaired children on the recognition of auditory shapes, and on the comparison between sighted and visually impaired adults in the integration of visual and haptic egocentric and allocentric frames of reference.

Further research seemed to be necessary to understand whether training based on auditory feedback might be useful for improving auditory shape perception (see Chapter 3).

Chapter 3

Technological systems to assess and rehabilitate spatial competence in sighted and visually impaired individuals

Chapter 2 investigated whether and how visual experience impacts on the development and consolidation of spatial coding skills by assessing humans' capability to integrate complementary reference frames based on the body (egocentric reference frame) and environmental (allocentric reference frame) landmarks. Overall, research findings indicate that visual feedback supports spatial development (Cappagli et al., 2015; Lepore et al., 2009; Maurer et al., 2005; Pasqualotto and Proulx, 2012; Ruotolo et al., 2012; Thinus-Blanc and Gaunet, 1997; Vasilyeva and Lourenco, 2010) and, specifically, it facilitates allocentric spatial coding (Newell et al., 2005; Newport et al., 2002; Postma et al., 2007). The original studies reported in Chapter 2 further confirm the role of vision on spatial competence, demonstrating that low vision affects the development of allocentric spatial coding in the visual domain, while blindness does not impact on the ability to switch from egocentric to allocentric coordinates in the haptic domain. Taken together, such results indicate that visual feedback typically facilitates the representation of spatial information in the brain, but when the visual feedback is permanently absent, as in the case of congenital blindness, compensatory mechanisms might support the refinement of haptic spatial capabilities. Moreover, such findings suggest that specific training based on multisensory stimulation should be adopted in the case of developmental visual disabilities (low vision and blindness), to overcome potential perceptual impairments in the spatial domain across development. Indeed, several pieces of evidence indicate that both low vision and blind children might show difficulties in performing auditory and haptic spatial tasks (Cappagli et al., 2015; Cappagli and Gori, 2016; Koustriava and Papadopoulos, 2012; Papadopoulos and Koustriava, 2011). Therefore, Chapter 3 aims to propose and validate new technological systems developed to assess and rehabilitate spatial capabilities, mainly designed to overcome the perceptual impairments observed in the visually impaired population.

3.1 Introduction

Spatial representation arises from the reciprocal relation between the perceiver and entities in the environment and the integration of spatially and temporally coherent multisensory inputs, which enhances spatial accuracy (Hart and Moore, 1973). Evidence indicates that vision has a pivotal role in integrating multisensory spatial information when stimuli are spatially and temporally congruent (Gori, 2015; Barry E. Stein and Meredith, 1993). For instance, the combination of visual-auditory (Miller, 1982) visual-tactile (Diederich et al., 2003) stimuli results in enhanced spatial and temporal discrimination abilities and shortens temporal reactions to an event (Miller, 1982; Todd, 1912). Moreover, it has been shown that audition and touch are strongly biased towards vision when conflicting spatial stimuli are provided, confirming that visual information typically dominates spatial perception (Alais and Burr, 2004; Anderson and Zahorik, 2011; Bertelson and Aschersleben, 2003; Botvinick and Cohen, 1998; Flanagan and Beltzner, 2000; Zahorik, 2001). Such evidence indicates that the absence of visual feedback during growth might determine spatial impairments in auditory (Cappagli et al., 2015; Cappagli and Gori, 2016; Fazzi et al., 2002), proprioceptive (Cappagli et al., 2015) and haptic (Gori et al., 2010) processing, as well as delays in motor capabilities (Fazzi et al., 2002; Hallemans et al., 2011; Levtzion-Korach et al., 2000). Vercillo and colleagues (2016), for example, have demonstrated that blind individuals have difficulties in spatial bisection tasks, which require the evaluation of spatial relationships between three consecutive and spatially distributed sounds. Moreover, several studies indicate that the absence of visual input might impair multisensory integration processing, preventing the consolidation of a mature spatial representation during development (Eimer, 2004; Van der Stoep et al., 2017). For these reasons, the development of technological devices to support visually impaired individuals in their spatial development would be a need. Nonetheless, despite the huge recent advancements in the 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 (Cuturi et al., 2016; Gori et al., 2016).

To overcome spatial impairments related to visual loss, in the past 20 years the role of audition in conveying spatial information has been linked to the development of Sensory Substitution Devices (SSDs), introduced as technological solutions that typically transform visual properties of a stimulus into auditory or tactile information (Bach-y-Rita and Kercel, 2003; Gori et al., 2016; Meijer, 1992; Proulx and Harder, 2008). For instance, substitution systems based on visual-to-tactile or visual-to-auditory conversion transform images captured by a camera into tactile or auditory stimulations directed to users, respectively (Auvray and Myin, 2009; Velázquez, 2010). Several works indicate that SSDs can support visually impaired individuals' daily life activities, e.g. by facilitating shape recognition with a device that transforms visual images into artificial soundscapes (Amedi et al., 2007). Nonetheless, the main reason why the visually impaired population does not accept SSDs is that they can be physically invasive in the sense that 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. In addition, the main reason why SSDs are not feasible for children is that they are based on artificial operating principles that young users find difficult to learn. For example, many substitution devices based on visual-to-auditory conversion pretend to convey information about luminosity using auditory parameters such as frequency levels, which results in an artificial procedure. Moreover, SSDs for the blind do not support the rehabilitation of impaired functions following visual loss, but they mainly aim at replacing the missing sensory information with other sensory signals (audition and touch) for daily activities such as object recognition. Finally, most of the SSDs developed so far substitute the visual function with either the auditory or the tactile modality alone, without providing multimodal stimulation whose benefits have been repeatedly reported compared to unimodal stimulation (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008).

Indeed, it has been demonstrated that multimodal stimulation is more effective than unimodal stimulation in providing spatial information of the environment mainly due to preexisting congruencies of information coming from the different senses (Bahrick et al., 2004;

Shams and Seitz, 2008). Specifically, the use of non-speech audio to represent information which is not audible otherwise, namely movement sonification (Kramer et al., 2010), consists in the auditory feedback of users' own movements and, thus, provides a multisensory representation of their own actions. According to Sensorimotor Contingency Theory (SCT) (O'Regan and Noë, 2001), the environment around an observer is not merely computed at the sensory level, but it is described through motor exploration (Clark, 2006), as in case of object recognition (Maye and Engel, 2011). For instance, Boyer et al. (2013) employed auditory feedback to provide blindfolded subjects with supplementary sensory information in addition to proprioception during a hand-pointing task, finding that such multisensory audio–motor coupling leads to enhanced pointing accuracy, demonstrating the efficiency of audition in on-line motor control. Furthermore, several studies have demonstrated that the use of audition to recalibrate spatial coding abilities typically developed through visual experience is effective in children (Cappagli et al., 2019, 2017) and adults (Finocchietti et al., 2017) with visual disabilities by performing training that associates auditory feedback to body movements. Nonetheless, rehabilitation training commonly adopted in visual disability is mostly unimodal as they tend to enhance the residual visual information through intensive and repetitive visual activities (Markowitz, 2016; Sabel et al., 1997). Conversely, positive outcomes of multisensory stimulation have been demonstrated in the case of individuals with partial visual deficits, indicating that audio-visual training can in fact facilitate long-lasting visuo-spatial functions (Bolognini et al., 2005; Cappagli et al., 2017; Frassinetti et al., 2005; Passamonti et al., 2009) and possibly produce long-term plastic changes (Grasso et al., 2016).

These results suggest that enriched experience with cross-modal stimulation can reinforce brain potential to perceive the multisensory nature of events. For such reasons, the creation and validation of technological devices to support the development of multisensory skills in visually impaired people would guarantee an improvement in autonomy and an increment of exploratory opportunities.

Chapter 3 presents and validates novel experimental tools to enhance multisensory integration and consolidate spatial competence in visual loss. More in detail, in the following sections, I will: introduce innovative technological tools developed to quantitatively assess and rehabilitate spatial competencies based on unisensory and multisensory stimulation (the *Tech*-systems and *ABBI* device, described in Section 3.2); investigate the efficacy of the proposed technological tool in conveying multisensory stimuli (Section 3.3.1) and the interaction with moving targets (Section 3.3.2); investigate the effect of a rehabilitation training performed with a proposed technological tool to enhance spatial skills in visually impaired (Section 3.3.4) and sighted (Section 3.3.3) individuals thanks to the sonification of body movements.

3.2 Technological development to foster multisensory stimulation with real-time feedback

In the context of a broader scientific collaboration between Istituto Italiano di Tecnologia (Genoa, Italy) and IRCCS Mondino Foundation (Pavia, Italy), I participated in the creation of a Joint-Lab whose main aim is to develop and validate a new technological platform designed to foster spatial development in children with visual impairments. The new platform called *Interactive GYM* (*i-GYM*) is meant as an interactive environment made of distinct multisensory tools to assess and train impaired perceptual functions from an early age:

- *Technological ARM* (TechARM): it is a wireless system consisting of separated but connectable units providing spatially and temporally-coherent multisensory stimulation on the body with real-time feedback from the user, in terms of temporal reaction and spatial localization;
- *Technological PAD* (TechPAD): it is a cabled system consisting of multiple TechARM units grouped in a unique and compact device, developed to investigate peripersonal spatial abilities outside the body and to implement experimental and clinical protocols in transverse and frontal plans;
- *Technological MAT* (TechMAT): it is a cabled system made of distinct but connectable modules that provide haptic, auditory and visual stimulation to create a technological multisensory carpet through which children can explore the surrounding extrapersonal space.

The technical development and core features of the new technological tools have been designed for the i-GYM: TechARM (Section 3.2.1), TechPAD (Section 3.2.2) and TechMAT (Section 3.2.3). Moreover, I will present the validation studies to test the efficacy of the first developed and ready-to-test tool (TechARM). Specifically, I will report two validation studies in which I investigated whether the TechARM system is an useful device to provide multisensory stimulation on the body with two main advantages derived from the connection of separate multisensory units. The first one is to increment the total size of the stimulated area, enhancing overall perceptual accuracy (Section 3.2.1.3), the second one is to provide dynamic multisensory stimulation on the body, creating the impression of moving targets (Section 3.2.1.4).

Concerning the design and technological development of the device ABBI (Audio Bracelet for Blind Interactions), it was carried out within the EU Strep project ABBI FP7-ICT 611452 ("https://www.abbiproject.eu/," n.d.). The main aim of ABBI is to improve spatial representation skills and to rehabilitate spatial and social deficits of individuals with visual impairment by exploiting a natural association between body movements and auditory feedback of body movements. Auditory feedback of body movements allows the visually impaired individual to associate movements with the limbs' spatial position and, consequently, to build an environmental representation of his/her body in an intuitive and direct manner (Finocchietti et al., 2015c; Porquis et al., 2017). ABBI has been validated in two separate studies with a three-months rehabilitation program, respectively, involving 3 to 5 years old (Cappagli et al., 2017) and 6-to-17 years old (Cappagli et al., 2019) visually impaired children. The rehabilitative sessions comprised spatial and social training exercises based on audio-motor coupling. The improvement observed in visually impaired patients was evaluated with specific spatial and motor tasks, further confirming the importance of multisensory training in case of sensory loss. The battery of ad-hoc tests used to assess the outcomes of the training with ABBI (Finocchietti et al., 2015c) required the use of complex experimental devices and the presence of a skilled experimenter. Therefore, to simplify the administration of the assessment tasks, the project comprised the development of ABBI-K, an innovative portable system consisting of a briefcase with a set of customized loudspeakers controlled by a dedicated Android application via Wi-Fi™ and two ABBI devices (Martolini et al., 2018), with the main aim to provide a more accessible and intuitive tool to simplify testing procedures.

3.2.1 TechARM

The TechARM system was designed as a set of multiple wearable, multisensory devices including: (i) embedded sensors and actuators to enable visual (V), auditory (A), and tactile (T) interactions, (ii) a capacitive (C) surface receiving inputs from the user, (iii) and an inertial (I) unit to detect position updates in real-time. Figure 3.1 shows the functioning scheme of a single unit of the TechARM system.

The system

The platform is implemented at bare-metal (firmware-level) to minimize latency, and it is based on an ATMEGA328P Micro-Controller Unit (Microchip Technology Inc.), that interfaced a two-channel CY8C20121 capacitive sensor (CapSense Express™, Cypress Semiconductor Corp.), a BNO055 I2C Inertial Module Unit (Adafruit Industries), a MAX1749 haptic moto-driver (Maxim Integrated Products), a WS2812 Red Green Blue (RGB) LED (WORLDSEMI Co.), a SSM2305RMZ speaker driver (Analog Devices Inc.), a nRF24L01 2.4GHz ISM transceiver (Nordic Semiconductor), and a microSD card holder. The prototype

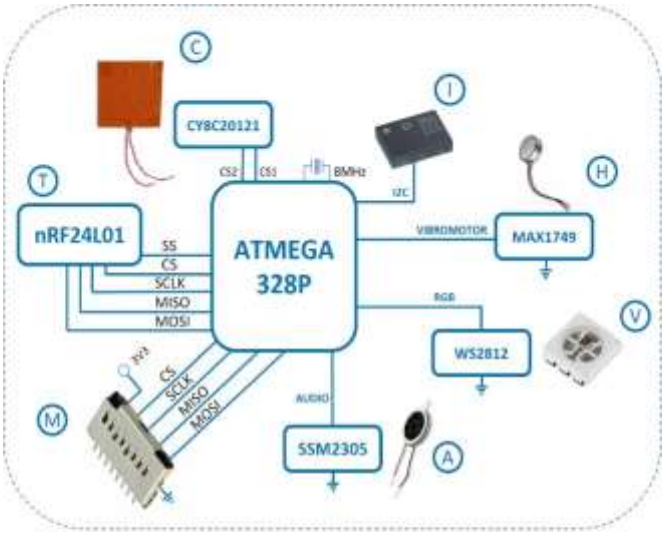

Figure 3.1 The TechARM functioning architecture.
Each unit of the system is based on an ATMEGA328P Micro-Controller Unit, that controls two-channels CY8C20121 capacitive sensor (C), a BNO055 I2C Inertial Module Unit (I), a MAX1749 haptic moto driver (H), a WS2812 Red Green Blue (RGB) LED (V), a SSM2305RMZ speaker driver (A), a nRF24L01 2.4GHz ISM transceiver (T), and a microSD card holder (M).

is provided with an internal Li-Po 160mAh battery. Figure 3.2 shows the prototype with its final biocompatible enclosure (top-left), battery charger (top–right), and internal PCB unit with detail on a few peripherals (bottom). A single unit's dimension was 25 mm x 25 mm x 25 mm, with the dimension of the upper sensitized area of 625 mm^2, and the enclosure is realized with a biocompatible photopolymerizing resin. The firmware is conceived to let the system be polled anytime to read-out the peripheral input data (touch detection and IMU data), and at the same time provide output events to the haptic, auditory and visual peripherals. The system is programmed and controlled with Matlab® through a serial port connection with the ISM transceiver. Devices addressing can reach up to 255 units, and it is possible to send separate commands to each input/output peripheral on each device simultaneously. The system is intended to create multisensory environments, using multiple units controlled separately and simultaneously. Compared to previously released multisensory systems (Gori et al., 2019) the devices can be distributed in different places inside a room or along the body, in parallel and multiple wireless connections. Moreover, the TechARM provides the possibility to detect a touch on the upper surface of each unit's enclosure and check position updates along the x-, y -, and z-axes in real-time.

Core features

- Communication and control. The ISM transceiver is centered on the ATMega328 microcontroller. It allows the communication between the PC and the TechARM via a virtual serial port from USB by transferring the signal to the nRF24L01+ radio module using

Figure 3.2 The TechARM single unit.
Dimensions of a single unit prototype are 2.5x2.5x2.5 cm, with biocompatible enclosure (top–left) and a battery charger (top–right). Both battery charger and enclosure are made of a photopolymerizing resin. An internal PCB unit presents a haptic motor, a touch-sensitive surface, a RGB LED, and a speaker as main peripherals (bottom).

  an SPI port. The USB port of the PC also provides the necessary power supply for the operation of the unit. The electronic board's dimensions enclosed in its plastic container are 45 mm x 50 mm x 8 mm. The Wi-Fi radio control module communicates with the transceiver, with dimensions 23 mm x 30 mm. This module includes an ATMega328 microcontroller, that transfers commands and I/O data to control the peripherals.

- Main microcontroller. The ATMega328 microcontroller receives via radio module and handles all the commands to be sent to the peripherals. Each peripheral is managed directly by I/O pins (sensors) or output (stimuli) and by SPI or I2C ports. This component is used at a reduced clock (8 MHz), guaranteeing low power consumption while allowing the fast reading of audio files.

- Peripherals:

- Capacitive sensor: it is obtained by using a single CY8C20121-SX1I module.
- Vibromotor: the vibration is produced by an eccentric micromotor (Precision Microdrives) with diameter 8 mm, thickness 3.4 mm, powered by MAX1749 haptic moto-driver to ensure a stable power supply.
- RGB LED: a high-brightness RGB-type composite LED is provided, producing a colored stimulus across the visible spectrum.
- Audio amplifier: a class-D digital amplifier of power 2W drives a mini-speaker (diameter 12 mm) to play the audio files stored in a 4GB microSD memory (Kingston Technology) and read by the microncontroller. The format of files is .afm, converted from .wav.
- Inertial Measurement Unit (IMU): the unit includes an accelerometer, a gyroscope and a magnetometer of great sensitivity and precision, equipped with self-calibration system and transmission of *quaternions*.
- ON/OFF button

- Power management. The TechARM units include Lithium-Ion rechargeable 160mAh batteries. Up to five units can be recharged using a full-custom charger integrating an array of blade-type power connectors and providing a 5V stable supply. The battery charger is realized using a biocompatible photopolymerizing resin.

3.2.2 TechPAD

The TechPAD system is designed as a matrix of 12 multisensory modules, independent from each other, arranged in a 4x3 array (dimensions: 430 mm x 325 mm) to assume the form of a tablet, for the use on a flat surface (e.g. a table). Figure 3.3 represents the appearance and utilization of the resulting multisensory tablet positioned in either horizontal or vertical planes.

The system

Each module is realized on a rigid printed circuit with dimensions 106 mm x 106 mm x 1.4 mm, and it includes (see Figure 3.4): (i) embedded sensors and actuators to enable visual (V), auditory (A), and tactile (T) interactions, (ii) and a capacitive (C) surface receiving inputs from the user. Each module of the matrix is equipped with 16 CY8CMBR2016-24LQXI capacitive touch sensors (CapSense Express™, Cypress Semiconductor Corp.; 8 mm x 8 mm squares), 4 loudspeakers (diameter 25 mm) controllable from 4 SSM2305CPZ audio amplifiers (Analog Devices Inc.), 8 WS2812 RGB LEDs (WORLDSEMI Co.), and 4 MAX1749 haptic

Figure 3.3 The TechPAD system.
Appearance of the multisensory TechPAD tablet, that can be positioned in either horizontal or vertical planes thanks to the tilting mechanical supporting structure.

moto-drivers (Maxim Integrated Products). The modules also control audio modules (TechPAD-Sound units), realized on a rigid printed circuit with dimensions 53 mm x 53 mm x 1.6 mm, that allows the setting of sound parameters and the reproduction of mono- or polyphonic sounds. The firmware is conceived to let the system be polled anytime to read-out the peripheral input data (touch detection), and at the same time provide output events to the haptic, auditory and visual peripherals. Ideally, modules addressing can reach up to 255 units, and different modules can receive synchronous commands to each input/output peripheral since each module is set with a unique address. The system is intended to create multisensory environments, using multiple units controlled separately and at the same time. The visual, audio and haptic peripherals of the modules are controlled by a RS485 transceiver, which is in turn controlled through a wired connection (serial port) from the PC. The system is programmed and controlled with the software Matlab®. A full-custom plastic and metal mechanical enclosure is realized to make the structure compact, support the internal components (modules and TechPAD-Sound units), and allow both a horizontal and vertical placement thanks to a tilting mechanical support provided with adjustable grips. The power supply is external to the system and provided via USB.

The core features

- Communication and control. The FTDI transceiver allows the communication between the PC and the remote matrix of multisensory modules. The transceiver receives commands from the PC via a virtual serial port, and it transfers information to the modules and the TechPAD-Sound units using the RS485 interface. An external power supply provides the

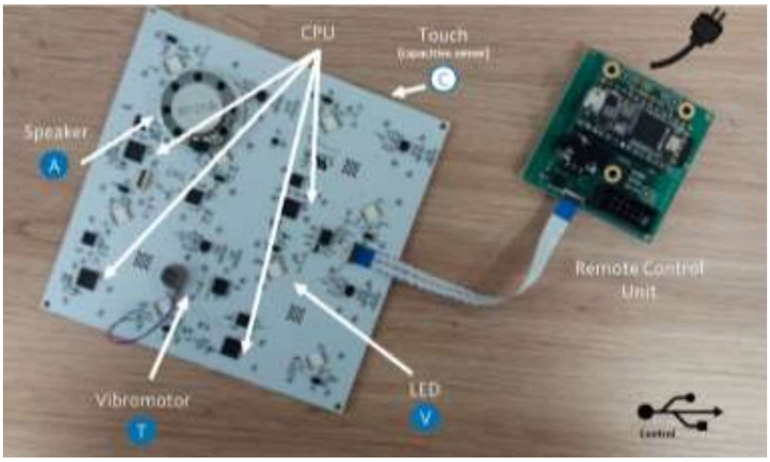

Figure 3.4 The TechPAD hardware components.
Each module of the TechPAD is realized on a rigid 106x106x1.4 mm printed circuit, and it includes: embedded sensors and actuators to enable visual (V), auditory (A), and tactile (T) interactions, and a capacitive (C) surface receiving inputs from the user. Each module of the matrix is equipped with 16 capacitive touch sensors, 4 loudspeakers, 8 RGB LEDs, and 4 haptic moto-drivers. The modules control also audio modules (TechPAD-Sound units), realized on a rigid 53x53x1.6 mm printed circuit, to set sound parameters and reproduce mono- or polyphonic sounds.

  necessary power for the operation of all units. The communication protocol guarantees the execution of commands in a few tens of microseconds. It also allows the activation and deactivation of multisensory stimuli and the reading of the peripherals' responses. Therefore, the microcontroller must verify that the command is intended for its module, execute it and return a response when requested.

- Modular microcontroller. Like the TechARM system, the ATMega328 microcontroller of the modules receives commands via the RS485 interface and handles all the commands sent to the peripherals. Each peripheral is managed directly by I/O pins (sensors) or output (stimuli) and by SPI or I2C ports. This component is used at a reduced clock (8 MHz), guaranteeing low power consumption while allowing the fast reading of audio files.

- <u>Peripherals</u>:

- Capacitive sensors: the 4 subsections within a single module contain 16 sensors, obtained by using 4 CY8CMBR2016-24LQXI modules.
- Vibromotors: the vibration is produced by 4 eccentric micromotors (Precision Microdrives) with diameter 8 mm, thickness 3.4 mm, powered by MAX1749 haptic moto-driver to ensure a stable power supply.
- RGB LEDs: 8 high-brightness RGB-type composite LEDs are provided, producing a colored stimulus across the visible spectrum.
- Audio amplifiers: 4 class-D digital amplifiers of power 2W drives 4 mini-speaker (diameter 25 mm) to play the audio files stored in a 4GB microSD memory (Kingston Technology) inside the dedicated cardholder on mounted on the corresponding TechPAD-Sound unit. The format of audio files is .wav.

- <u>Power management</u>. The TechPAD is not provided with a battery on-board, since the necessary power supply is provided by an external charger certified for medical use, guaranteeing 220Vac input and 5Vdc 2A output.

3.2.3 TechMAT

The TechMAT design is intended as a unique squared multisensory module (dimensions: 500 mm x 500 mm), potentially connectable with other independent modules (Figure 3.5).

The system

The module includes (see Figure 3.6): (i) embedded sensors and actuators to enable visual (V), auditory (A), and tactile (T) interactions, (ii) and a capacitive (C) surface receiving inputs from the user. It is equipped with 4 loudspeakers (diameter 20 mm), controllable from 4 SSM2305CPZ audio amplifiers (Analog Devices Inc.), 8 WS2812 RGB LEDs (WORLDSEMI Co.), and 8 MAX1749 haptic moto-drivers (Maxim Integrated Products). Accessory audio modules (TechMAT-Sound units), corresponding to each digital amplifier and realized on a rigid printed circuit, allow the setting of sound parameters and the reproduction of mono- or polyphonic sounds. The TechMAT-Sound unit is provided with a local microcontroller (MK20DX259VLHT 96MHz + SGTL5000), which is seen by the remote PC as an independent peripheral with a unique address. The system is intended to create multisensory events, using

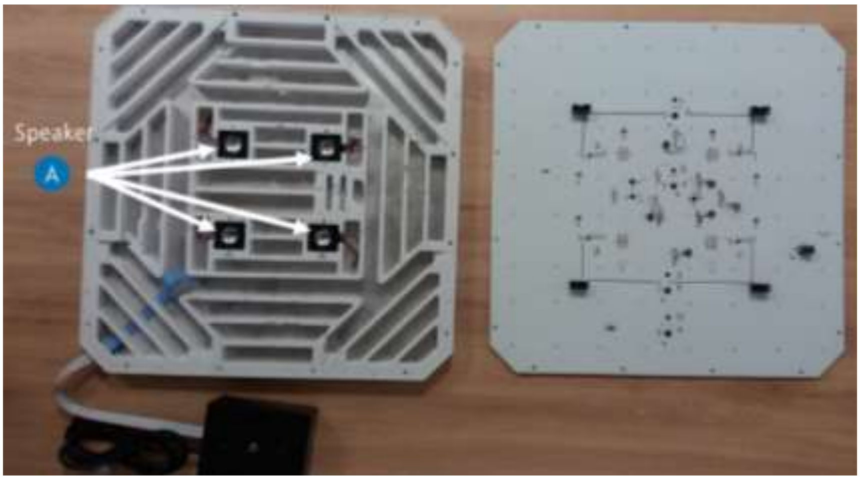

Figure 3.5 The TechMAT system.
Appearance of a single multisensory TechMAT tile, that can be mounted with other modules through cabled connections. It includes 4 speakers (A) producing auditory stimuli.

multiple peripherals controlled separately and at the same time. The visual, audio and haptic peripherals are controlled by a RS485 transceiver, which is in turn controlled through a wired connection (serial port) from the PC. The system is programmed and controlled with the software Matlab®. A full-custom metal mechanical enclosure is realized to make the structure compact, support the internal components (TechMAT-Sound units), and guarantee mechanical solidity and resistance as a walkable floor. The power supply is external to the system and provided via USB. The TechMAT system is still at a prototyping level. The next step implies testing the pressure sensors to be included to obtain specific and precise pressure feedback.

The core features

- Communication and control. The FTDI transceiver allows the communication between the PC and all the remote modular units of the TechMAT system. The transceiver receives commands from the PC via a virtual serial port, and it transfers information to the modules and the TechMAT-Sound units using the RS485 interface. An external power supply provides the necessary power for the operation of all units.
- Modular microcontroller. As for the two previous Tech- systems, the ATMega328P microcontroller receives commands via the RS485 interface and handles all the commands to be sent to the peripherals. Each peripheral is managed directly by I/O pins (sensors) or output (stimuli) and by SPI or I2C ports. This component is used at a reduced clock (8 MHz), guaranteeing low power consumption while allowing the fast reading of audio files. Furthermore, interfacing with pressure sensors is foreseen.

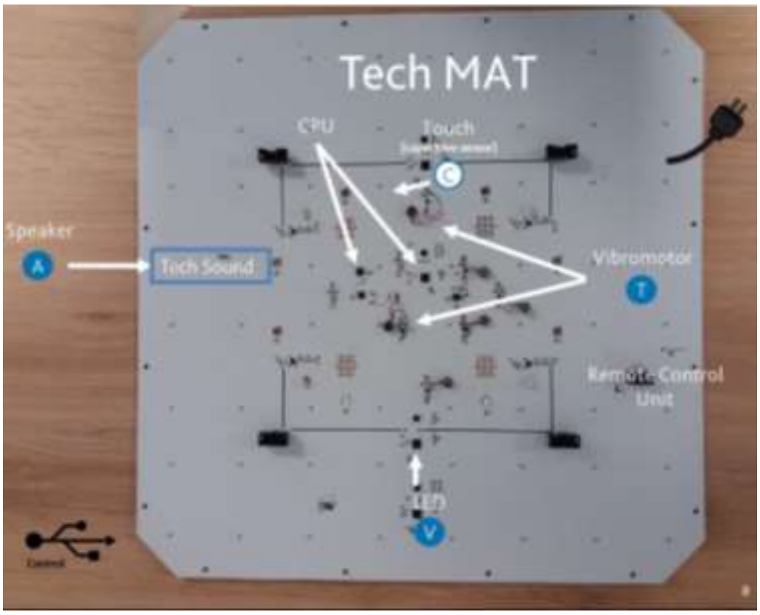

Figure 3.6 The TechMAT hardware components.
The TechMAT is realized as a unique squared 500x500 mm printed circuit, and it includes: embedded sensors and actuators to enable visual (V), auditory (A), and tactile (T) interactions, and haptic (C) surface receiving inputs from the user. Each module of the matrix is equipped with 4 loudspeakers, 8 RGB LEDs, and 8 haptic moto-drivers. The module controls also a remote audio control unit (TechMAT-Sound unit), to set sound parameters and reproduce mono- or polyphonic sounds.

- Peripherals:
- Pressure sensors: the pressure sensors need a further testing phase.
- Vibromotors: the vibration is produced by 8 eccentric micromotors (Precision Microdrives) with diameter 8 mm, thickness 3.4 mm, powered by MAX1749 haptic moto-driver to ensure a stable power supply.
- RGB LEDs: 8 high-brightness RGB-type composite LEDs are provided, producing a colored stimulus across the visible spectrum.
- Audio amplifiers: 4 class-D digital amplifiers of power 2W drives 4 mini-speaker (diameter 20 mm) to play the audio files stored in a 4GB microSD memory (Kingston Technology) inside the dedicated card holder on mounted on the corresponding TechMAT-Sound unit. The format of files is .afm, converted from .wav.

- Power management. As in the case of the TechPAD, the TechMAT is not provided with a battery on-board, since the necessary power supply is provided by an external charger certified for medical use, guaranteeing 220Vac input and 5Vdc 2A output.

3.2.4 ABBI

The design and technological development of the device ABBI (Audio Bracelet for Blind Interactions; see Figure 3.7) was carried out within the EU Strep project ABBI FP7-ICT 611452 ("https://www.abbiproject.eu/"). The main aim of ABBI is to improve spatial representation skills and to rehabilitate spatial and social deficits of individuals with visual impairment by exploiting a natural association between body movements and auditory feedback of body movements. Auditory feedback of body movements allows the visually impaired individual to associate movements with the limbs' spatial position and, consequently, to build an environmental representation of his/her body in an intuitive and direct manner (Finocchietti et al., 2015c; Porquis et al., 2017). ABBI has been validated in two separate

Figure 3.7 The ABBI device.
Appearance of the wearable and wireless 55x35x25 mm device called ABBI (Audio Bracelet for Blind Interactions), carried out within the EU Strep project ABBI FP7-ICT 611452, with the aim to improve spatial representation skills in individuals with visual impairment by auditory feedback of body movements.

studies with a three-months rehabilitation program, respectively, involving 3 to 5 years old (Cappagli et al., 2017) and 6-to-17 years old (Cappagli et al., 2019) visually impaired children. The rehabilitative sessions comprised spatial and social training exercises based on audio-motor coupling. The improvement observed in visually impaired patients was evaluated with specific spatial and motor tasks, further confirming the importance of multisensory training in case of sensory loss.

The battery of ad-hoc tests used to assess the outcomes of the training with ABBI (Finocchietti et al., 2015c) required the use of complex experimental devices and the presence of a skilled experimenter. Therefore, to simplify the administration of the assessment tasks, the project comprised the development of ABBI-K, an innovative portable system consisting of a briefcase with a set of customized loudspeakers controlled by a dedicated Android application via Wi-Fi™ and two ABBI devices (Martolini et al., 2018), with the main aim to provide a more accessible and intuitive tool to simplify testing procedures.

The system

As explained in the work by Martolini and colleagues (2018), ABBI-K's main intent is to overcome the limits of previous experimental systems to assess spatial and motor skills in visually impaired children and adults under rehabilitative training with ABBI. The system includes (see Figure 3.8) 10 independent Wi-Fi™ loudspeakers, a smartphone with the “ABBI-K” Android application, two hub USB 7-ports rechargers with relative power supplies to recharge simultaneously multiple devices, and two ABBI devices. The smartphone is unusable to call, send SMS and mobile data connection, to be dedicated only to experimental purposes. In this way, the system replaced a PC with a smartphone with an easy-to-use application onboard.

Each ABBI in the system (see Figure 3.9) is wearable and wireless device controlled by a smartphone application via Bluetooth Low Energy. The dimensions (55mm x 35mm x 25mm) and weight (40 g) make it easy to mount on a wristband adapted to children’s upper limbs. The system hardware is formed by a custom-designed electronic circuit, a battery and micro-speaker and/or headset connector. The high-density six-layer circuit includes a powerful

Figure 3.8 The ABBI-K system.
Appearance of the ABBI-K system, an innovative portable tool with a briefcase including a set of customized loudspeakers controlled by a dedicated Android application via Wi-Fi™, a 7-ports hub usb to recharge batteries of multiple components, and two ABBI devices, with the aim to provide a more accessible and intuitive tool to simplify testing procedures.

microcontroller (ARM®-based Cortex® M3 STM32L151QDH6, ST Microelectronics), an audio class-D amplifier (SSM2305, Analog Devices Inc.), a Bluetooth™ low-energy module (BLE113-A, Bluegiga Technologies), an Inertial Motion Unit (IMU) that includes a three-axis gyroscope (A3G4250D, ST Microelectronics) and a six-axis accelerometer/magnetometer combo (LSM303D, ST Microelectronics), a 2x8 MB Flash memories (S25FL064P, Spansion) to store audio files and/or log the activity of the user, a micro-USB connector to charge the battery (Coin cell LIR 2450, rechargeable lithium-ion), update the firmware and upload/download large files. A RGB LED is provided to indicate when ABBI is powered on (blue light), when it is charging (red light), and when it is muted (yellow light) from the smartphone application or by pushing the lateral button on the enclosure. The external enclosure is made of an opaque photopolymer material (VeroWhite, Stratasys) or a clear bio-compatible Objet FullCure®360, in order to guarantee biocompatibility. Sounds are synthesized inside the microcontroller that runs an embedded program. Generated sounds can be a combination of continuous tones, intermittent beeps, or audio files. The inertial sensors provide movement data, which are used for triggering or modulating the sounds. The wireless module is the connectivity link for remote controlling the bracelet, such as configuring its operating

Figure 3.9 ABBI hardware components.
The ABBI system hardware includes a custom-designed electronic circuit with a Bluetooth™ low-energy module, to connect the device to the smartphone, and an Inertial Motion Unit (IMU) that includes a three-axis gyroscope, and a six-axis accelerometer/magnetometer combo, a Li-Ion battery and a micro-speaker.

modes (motion-triggered or remote controlled), muting it, or adjusting its volume. In the remote-control modality, the sound onset and offset can be controlled remotely via the smartphone or PC. In the movement-triggered modality, the sound starts automatically when the device velocity overcomes a pre-set threshold, and it stops when the velocity is below this limit.

The core features

- Loudspeakers. The 10 loudspeakers that are part of the ABBI-K system assume the technical name SUWA (Set-Up Wi-Fi Audio), with dimensions 60 mm x 60 mm x 6.5 mm. Each peripheral is independent of the others, thanks to the unique IP address. The devices are provided with a conductive layer (capacitive sensors) for touch detection on the upper surface in specific tasks and two independent LEDs to indicate when the loudspeaker is active (blue light) and the battery status (yellow light). Each loudspeaker is powered by a Li-Ion 3.7 V 1500 mA rechargeable battery, recharged via a microUSB port. The standby current consumption of the battery evaluated at 3.7 V is less than 90 mAh. The electronic board's principal components are the Arduino Pro Mini ATmega328 microcontroller, a Wi-Fi™ ESP8266 module, two analog capacitive sensors, a class-D audio mono amplifier, a digital potentiometer, a voltage regulator, a charging battery Integrated Circuit, and a micro-SD.
- Communication and control. The ESP module mounted on the electronic board of each loudspeaker is dedicated to the connection with the access point gateway generated on the smartphone. The loudspeakers are distinguished by different IP addresses, including a tracking progressive number from 100 to 109, and a unique socket port (9000). After the connection, a series of commands are sent to the Arduino microcontroller on the electronic board. Each ABBI device communicates with the smartphone via a Bluetooth LE module, a standard protocol implemented for low power applications. The velocity of data communication is around 10 kB/s, which is ideal for adjusting the device's parameters. ABBI is designed to send advertisements of availability and respond to connection requests from the smartphone. When the device is connected to the smartphone, the user can configure the audio and motion characteristics of ABBI, e.g. changing the type of sound, the volume of the sound, broadcasting motion data.
- Power management. The main consumer of battery power concerns the sound production of the ABBI devices, which is up to 320 mAh for a continuous sound at maximum volume. The choice to use intermittent sounds can minimize power consumption. To save power, ABBI activates the sleep modality automatically after a certain period without being moved

- (e.g., 20 s), and wakes up automatically when movements above a defined threshold are detected. The Bluetooth module starts working exclusively when ABBI sends advertisements. Once the Bluetooth connection is over, the Bluetooth module goes back into sleep mode. All these transitions are managed via a state machine in the firmware (the microcontroller's embedded program).

3.3 Validation of the technology for assessment and rehabilitative purposes

In the following Sections, I will report two studies in which I investigated whether the use of the TechARM system as an innovative technological aid would guarantee an efficient and reliable assessment of spatial competencies, specifically the effects of stimulated area's size (Section 3.3.1) and the interaction with moving targets (Section 3.3.2) when unisensory and multisensory stimuli are conveyed on the body. Then, I will report two studies in which I assessed whether the use of ABBI would improve spatial coding abilities in temporal or permanent absence of vision, specifically the effects of an audio-motor training on the recognition of auditory shapes in sighted adults (Section 3.3.3) and on auditory and proprioceptive competencies in long-term late blind adults (Section 3.3.4).

3.3.1 Assessment of increasing stimulated area’s effects in unisensory and multisensory conditions

The present study has been carried out to assess the efficacy of the Tech-ARM in incrementing the total size of stimulated area and enhancing overall perceptual accuracy. Indeed, it has been demonstrated that multisensory stimulation enhances sensory accuracy, but no study to date has explored whether also the size of the stimulated area affects perceptual performance. If increasing the size of stimulation positively impacts overall sensory accuracy, this would be a crucial factor to consider when developing technological tools to foster multisensory development in rehabilitation contexts.

Several pieces of evidence indicated that both spatial and temporal proximity affects multisensory integration. Stevenson and colleagues (2012) showed that for asynchronous and synchronous audio-visual stimuli, reaction times increased and decreased, confirming that temporal proximity facilitates multisensory integration. Moreover, the effects of temporal proximity depend on the stimulated spatial area. The space outside the body is divided into peripersonal (i.e., immediately around the body; (Brain, 1941; Hall, 1966; Previc, 1998; Rizzolatti et al., 1981)) and extrapersonal (i.e., beyond the peripersonal region; (Hall, 1966)) spatial areas. Sambo and Foster (2009) demonstrated decreased reaction times to simultaneous visuo-haptic stimulation only when stimulation occurred in the peripersonal space. Several studies have also demonstrated that spatial proximity of unisensory stimulation promotes a statistically optimal sensory integration (Ernst and Banks, 2002; Soto-Faraco et al., 2002; Spence and Squire, 2003; Zampini et al., 2003). However, it is not clear whether the size of sensory stimulation can affect perceptual accuracy, specifically whether incrementing the overall sensory stimulated area with multiple spatially and temporally coincident stimuli would enhance or impoverish sensory discrimination. This effect is referred to the impact of of the stimulated area's size on the perceived intensity of a stimulation. Therefore, positive results would indicate that the bigger the surface area stimulated, the higher the accuracy in the stimulation's perception. Similarly, the spatial summation effects have been demonstrated at the perceptual level, e.g. for different visual stimuli (Anderson and Burr, 1991, 1987; Burr et al., 1998), tactile stimuli (Gescheider et al., 2002; Verrillo et al., 1999; Verrillo and Gescheider, 1975) and pain stimuli (Marchand and Arsenault, 2002), and at the cortical level, e.g. in the visual cortex areas (Shushruth et al., 2009), suggesting its potential role for several perceptual mechanisms. Moreover, several pieces of evidence have demonstrated that spatial summation effects might explain several psychophysical phenomena, e.g. contextual effects (Levitt and Lund, 1997; Li et al., 1999).

In the present study, we investigated the relationship between the size of the stimulated surface and sensory discrimination by assessing how the size of sensory stimulation influences perception in unimodal (visual, auditory, tactile) and multimodal (bimodal, trimodal) conditions. We asked participants to tap a sensitized surface with the right index finger as soon as they perceived unimodal (visual, auditory, or tactile) or multimodal (the combination of unimodal stimuli) stimulations. The stimuli were conveyed by multisensory units positioned on the left harm. Then, they were asked to verbally indicate the number of stimuli perceived, independently of the stimulus modality. To perform the task, we used the TechARM (see Chapter 3, Section 3.2.1), which is a wearable and wireless system that provides spatially- and temporally-coherent multisensory stimulation with real-time feedback from the user (Schiatti et al., 2020).

We hypothesized incrementing the stimulated area would decrease sensory threshold, thus increase sensory discrimination, both in unisensory and multisensory conditions. Moreover, due to the dominance of vision in spatial perception, we expected that visual information would dominate multimodal stimulation. Specifically, vision relies on a reference system based on external landmarks and facilitates spatial representation in allocentric coordinates. Therefore, we hypothesized that vision would promote the interaction of multiple stimuli conveyed on an increasing stimulated area of the body and enhance sensory accuracy more than modalities based on an egocentric perspective of space (e.g. touch). Indeed, we hypothesized that the absence of visual inputs would undermine an effective interaction between auditory and tactile stimulations, irrespective of the size of stimulated area.

Sample

Sixteen sighted adults between 25 and 37 years of age (mean age: 29 ± 0.82 years, 10 females) were enrolled in the study. Participants were randomly recruited by Istituto Italiano di Tecnologia (Genoa, Italy), which provided them with monetary compensation for their participation. Participants belong to middle and upper-class Caucasian families living in a university town in Italy and none of them reported visual, auditory, musculoskeletal or neurological impairments. The study was approved by the local Ethics Committee (Comitato Etico ASL3, Genoa, Italy), and participants gave written consent to the experimental protocol, following the Declaration of Helsinki. The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.18 (Cohen's d = 1.09; see Schiatti et al., 2020);
- α err. prob. = 0.05;
- power (1-β err. prob.) = 0.95.

Task and procedure

The experiment was conducted in a dark room, where participants sat in front of a table. The experimental setup consisted of five multisensory units, part of the TechARM system (see Chapter 3, Section 3.2.1). Each unit included embedded sensors and actuators to enable visual

(RGB LED), auditory (digital amplifier and speaker), and tactile (haptic moto-driver) interactions and a capacitive surface (capacitive sensor) on the device's upper part to receive and record real-time inputs from the user (dimension of a single unit: 2.5 cm x 2.5 cm x 2.5 cm; dimension of upper sensitized area: 6.25 cm^2). Four units were shaped in a 2x2 array and positioned on participants' left arm, which was centrally aligned with their head, while the fifth unit was placed on the table, next to the right index finger. The dimension of the stimulation area was in the range from 6.25 cm^2 (single unit: 2.5x2.5 cm^2) to 25 cm^2 (four units) (Figure

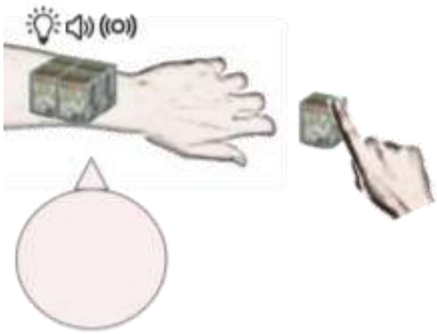

Figure 3.10 Experimental setup of the increasing stimulated area task.
The system used for the increasing stimulated area task consists in a technological system providing spatially- and temporally-coherent multisensory stimulation with real-time feedback from the user. Four units of the system are shaped in a 2x2 array and positioned on participants' left arm, with the head centrally aligned. Another unit is placed on the table, next to the right index finger, to record reaction times by tapping the upper sensitized surface. The dimensions of each unit are 2.5x2.5 cm2, for a total of 25 cm2 with four units.

3.10). During each trial, unimodal (auditory, visual, or tactile), bimodal (audio-tactile, audio-visual, tactile-visual) or trimodal (audio-tactile-visual) stimuli with a duration of 100 ms were randomly produced by a randomized number of units in the array (between one and four active units), defined by fifteen configurations. The active units produced the same temporally-congruent stimulation. Auditory stimuli were provided as 79 dB white noise burst at 300 Hz , visual stimuli were produced as white light by RGB LED (luminance: 317 mcd), and tactile stimuli were conveyed by a vibromotor peripheral (vibration frequency: 10 Hz). The experimental protocol was divided into two phases: a) a perceptual phase, where participants were asked to tap the upper surface of the fifth unit with the right index finger as soon as they where they reported verbally how many devices they assumed as active. Each stimulation was reproduced three times in all configurations, with a total amount of 315 trials (forty-five trials per seven stimulation levels). The experiment was performed in about one hour, and short breaks perceived a stimulus, regardless of the kind of stimulation conveyed; b) a cognitive phase, were allowed at any time during the session.

Data analysis and statistics

The experiment was designed to evaluate: a) the accuracy in determining the number of active units; b) the responsiveness to different levels of stimulation on the body. As a measure of accuracy, we computed index correct (IC), calculated as the number of correct responses divided by the total number of trials for each configuration of stimuli, and expressed as an index between 0 and 1. As a measure of responsiveness, we collected reaction times (RT), calculated as the time interval between the beginning of the delivered stimulation and the time when the participant tapped the fifth unit with the right index finger and expressed in seconds (s). To evaluate whether data were normally distributed, we applied the Shapiro-Wilk test of normality with the free software R (Free Software Foundation, Boston, MA, United States). After verifying that the data did not follow a normal distribution, we ran the analysis using nonparametric statistics. We conducted two separate two-ways permuted ANOVAs with *IC* and *RT* as dependent variables, and within-factors "*stimulation*" (seven levels: Auditory - A, Visual - V, Tactile - T, Audio-Tactile - AT, Audio-Visual - AV, Tactile-Visual – TV, and Audio-Tactile-Visual - ATV) and "*active units*" (four levels: One, Two, Three, and Four) as independent variables. The permuted Bonferroni correction for nonparametric data was applied in case of significant effects to adjust the p-value of multiple comparisons (significant value: $\alpha = .05$).

Results

We carried out two levels of analysis: i) the main effects of the increase of stimulated area and the types of stimulation provided on index correct (IC) and reaction times (RT); ii) the interaction effects between increasing stimulated area and the kind of stimuli on IC and RT.

In the first level of analysis, we examined whether the increasing number of active units and the difference between stimuli affected the performance in terms of accuracy (IC) and responsiveness (RT). As shown in Figure 3.11, the dimension of stimulated area resulted in a significant reduction of IC only within 18.75 cm2, with a similar performance in case of three and four active units, independently of the kind of stimulus provided (main effect: active units; RSS = 21.91, iter = 5000, $p < 2.2e{-}16$; and Bonferroni: One vs. Two = One vs. Three = One vs. Four = Two vs. Three: $p = 0.00$; Two vs. Four: $p = 0.89$; Three vs. Four: $p = 1$). Differently from IC, reactions to stimuli linearly increased with the increasing number of sources (main effect: active units; RSS = 4.57, iter = 5000, $p < 2.2e–16$; and Bonferroni: One vs. Two: $p = 0.02$; One vs. Three = One vs. Four: $p < 0.001$; Two vs. Three = Two vs. Four: $p < 0.001$; Three vs. Four: $p = 0.008$). The presence of visual stimuli, alone (unimodal) or combined with auditory or/and tactile stimuli (bimodal, trimodal), increased the response correctness, while unimodal auditory, tactile and bimodal audio-tactile stimuli induced a lower accuracy, regardless of the stimulated surface (main effect: stimulation; RSS = 197.73, iter = 5000, $p < 2.2e–16$; and Bonferroni: V/AV/TV/ATV vs. A/T/AT: $p < 0.001$). Concerning RTs, they were similar with unimodal tactile and bimodal visuo-tactile stimuli (Bonferroni: $p = 1$) but higher than with other stimuli, apart from modality and number of active units (Bonferroni: T vs. A: $p = 0.017$; T vs. V: $p = 0.004$; T vs. AT: $p = 0.025$; T vs. AV: $p < 0.001$; T vs. ATV: $p < 0.001$; TV vs. A: $p = 0.004$; TV vs. V/AT/AV: $p < 0.001$). The second level of analysis investigated

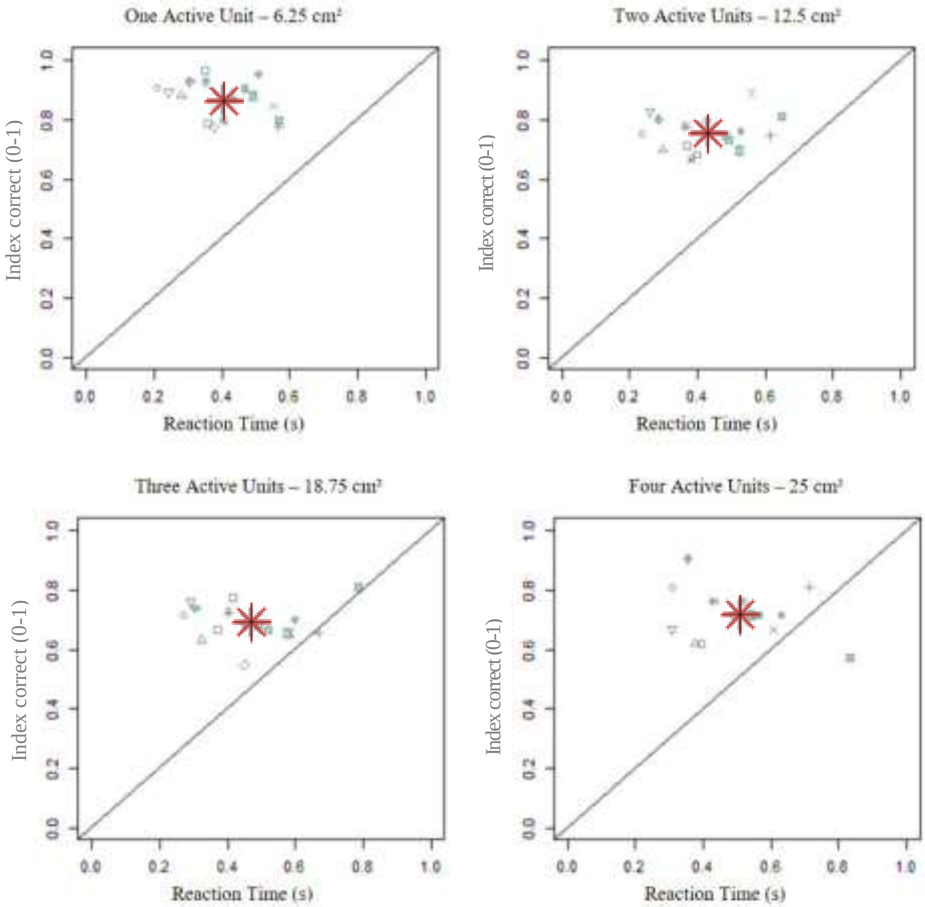

Figure 3.11 Impact of increasing stimulated area on index correct (IC) and Reaction Time (RT). The grey symbols represent the values of index correct (y-axis) between 0 and 1, as a function of Reaction Time (x-axis), expressed in seconds, per participant. The red asterisk is the average on the total number of participants. The black dashed lines indicate the chance level (0.25). The increase in the number of active units significantly resulted in a reduction of IC within 18.75 cm^2 ($p < 0.001$), along with a linear increase of RT until 25 cm^2 ($p < 0.001$).

whether the combination of the two factors might influence participants' performance and responsiveness. Firstly, we compared unimodal stimuli by considering changes in IC and RT while increasing the stimulated area. Figure 3.12A shows that the number of correct responses remained high only in case of visual stimuli (interaction between stimulation x active units; RSS = 45.04, iter = 5000, $p < 2.2e{-16}$; and Bonferroni: p = 1), while it linearly decreased with the increase in the number of active units for auditory (Bonferroni: A-One vs. A-Two/Three/Four: $p < 0.001$; A-Two vs. A-Three: $p = 0.049$) and tactile stimuli (Bonferroni: T-One vs. T-Two/Three/Four: $p < 0.001$; T-Two vs. T-Three: $p < 0.001$; T-Two vs. T-Four: $p = 0.007$). On the contrary, participants slowed down reactions to visual (interaction between stimulation x active units; RSS = 3.12, iter = 5000, $p < 2.2e{-16}$; and Bonferroni: V-One vs. V-Three/Four: $p < 0.001$; V-Two vs. V-Four: $p = 0.004$) but not to auditory (Bonferroni: $p = 1$) and tactile (Bonferroni: $p = 1$) stimuli (see Figure 3.12B). According to these findings, we may conclude that increasing the stimulated area did not affect discrimination accuracy when vision was present but negatively impacted on audition and touch, while it had a cost in terms of responsiveness only for visual stimuli. Secondly, we analyzed IC and RT's trend in bimodal and trimodal stimuli with increasing active units. As shown in the first level of analysis, Figure 3.12C highlights that vision combined with other stimuli improved the performance in terms of correctness (Bonferroni: $p = 1$), although a linear delay in responsiveness (see Figure 3.12D) was confirmed (Bonferroni: AV-One vs. AV-Two: $p = 0.005$; AV-One vs. AV-Three/Four: $p < 0.001$; AV-Two vs. AV-Four: $p < 0.001$; AV-Three vs. AV-Four: $p = 0.037$; TV-One vs. TV-Two: $p = 0.024$; ATV-One/Two vs. ATV-Three/Four: $p < 0.001$; ATV-Three vs. ATV-Four: $p = 0.026$). Concerning audio-tactile stimuli, the absence of significant differences between different dimensions of stimulated area was observed for both IC (Bonferroni: AT-One vs. AT-Two/Four: $p = 1$; AT-One vs. AT-Three: $p = 0.72$; AT-Two vs. AT-Three/Four: $p = 1$; AT-Three vs. AT- Four: $p = 0.19$) and RT (Bonferroni: AT-One vs. AT-Two: $p = 1$; AT-One vs. AT-Three: $p = 0.88$; AT-One vs. AT-Four: $p = 0.96$; AT-Two vs. AT-Three/Four: $p = 1$; AT-Three vs. AT- Four: $p = 1$). Finally, to deeply evaluate the interaction between auditory and tactile stimuli, we compared the performance with unimodal and bimodal conditions (Figure 3.13). Results showed that IC was lower with bimodal than both unimodal stimulations for the smallest dimension of stimulated area (6.25 cm^2) (Bonferroni: $p < 0.001$). However, accuracy with audio-tactile stimuli surprisingly increased in the case of three active units (18.75 cm^2), overtaking only auditory stimulation (Bonferroni: AT vs. A: $p < 0.001$; AT vs. T: $p =$

1.00), that was even lower than tactile stimulation (Bonferroni: T vs. A: $p = 0.038$; see Figure

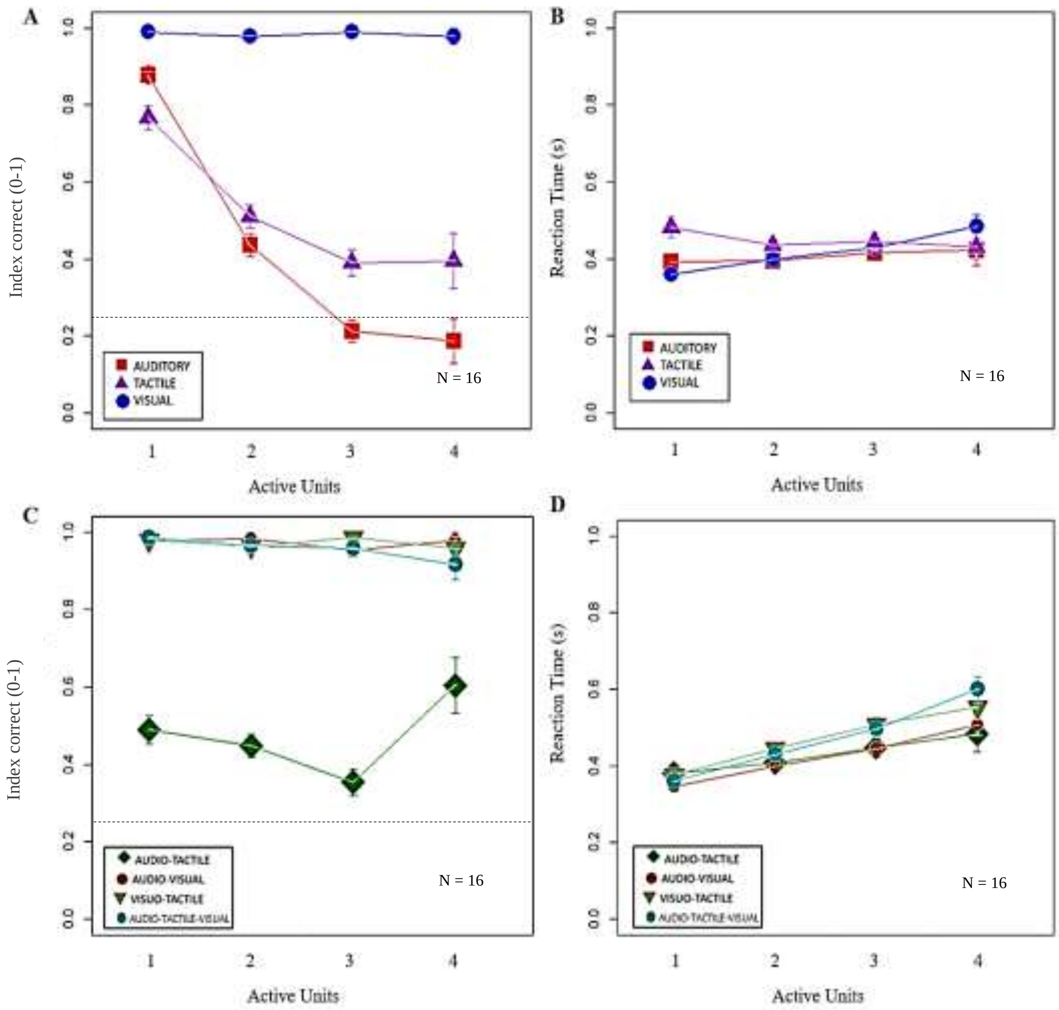

Figure 3.12 Impact of increasing stimulated area on index correct (IC) and Reaction Time (RT) with unimodal and multimodal stimuli.
In **A)** and **B)** each symbol represents the mean value with standard error of IC and RT (y-axis), respectively, obtained by all the participants per number of active units (x-axis) with unimodal visual (blue dots), auditory (red squares) and tactile stimuli (purple triangles). The black dashed lines indicate the chance level (0.25). **A)** Only visual stimuli induced a high IC ($p = 1$), regardless of the number of active units, with respect to the linear decrease of auditory ($p < 0.05$) and tactile ($p < 0.01$) modalities. **B)** Concerning RT, a linear increase in responsiveness was present in case of visual stimuli ($p < 0.01$), but not auditory or tactile stimuli ($p = 1$). In **C)** and **D)** each symbol represents the mean value with standard error of CS and RT (y-axis), respectively, obtained by all the participants per number of active units (x-axis) with bimodal audio-tactile (green rectangle), audio-visual (dark-red dots), and visuo-tactile (red and green triangle) stimuli, and with trimodal audio-tactile-visual (light-blue dots) stimuli. **C)** When bimodal conditions included visual stimuli, IC maintained a high value, independently from the number of active units ($p = 1$), while IC were lower for audio-tactile stimuli with no significant differences between different dimensions of stimulated areas ($p > 0.10$). **D)** As opposite to the trend of IC, RT linearly delayed only in presence of visual stimuli ($p < 0.05$), while no significant difference was experienced with audio-tactile stimuli ($p > 0.80$).

3.12A). These findings might point out that bimodal interaction of audio-tactile stimuli occurred with increased stimulation complexity.

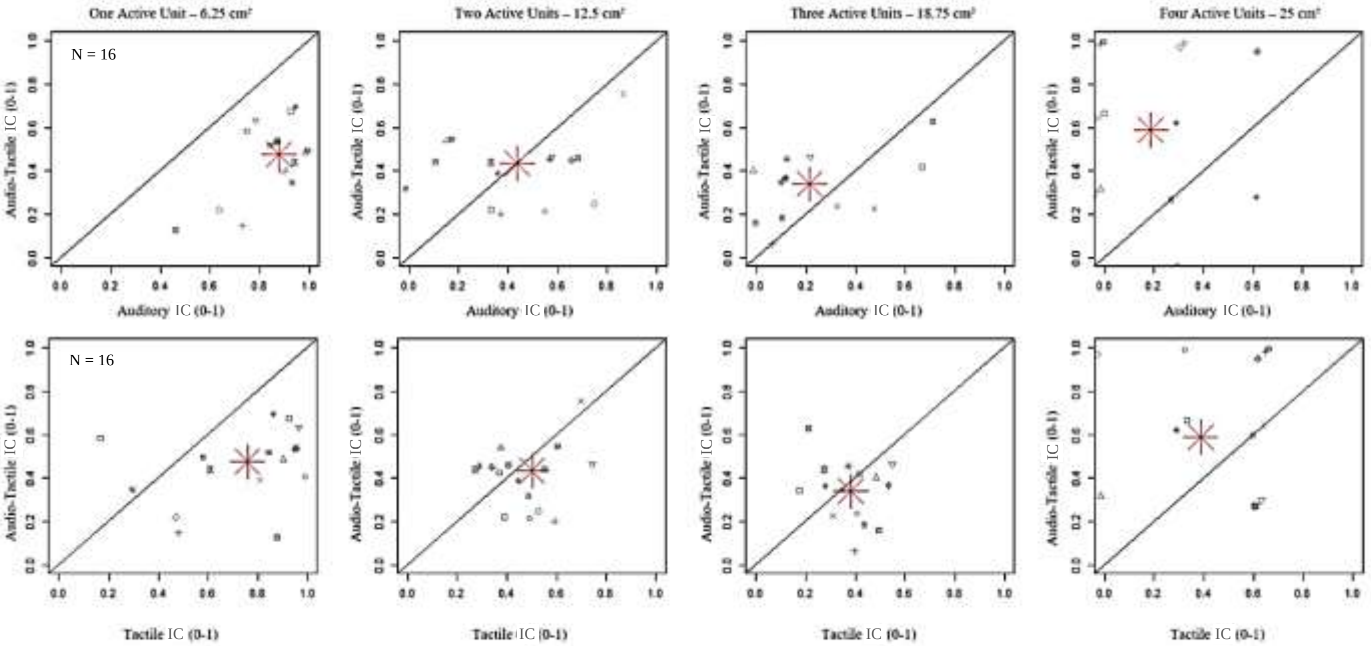

Figure 3.13 Comparison of index correct (IC) between bimodal Audio-Tactile stimuli and unimodal Auditory and Tactile stimuli.
The grey symbols represent the values of index correct in the Audio-Tactile modality (y-axis), expressed as an index between 0 and 1, as a function of index correct in the Auditory and Tactile modalities (x-axis), expressed as an index between 0 and 1, per participant. The red asterisk is the average on the total number of participants. IC was lower with bimodal than both unimodal stimulations when one unit was active (6.25 cm^2) ($p < 0.001$), while it increased until 18.75 cm^2 with a significant difference with respect to Auditory ($p < 0.001$) but not Tactile ($p = 1.00$) stimuli.

Discussion

The present study aims to unravel the mechanisms responsible for unisensory and multisensory spatial interaction. Specifically, it investigates whether the stimulated area's increase has a detrimental or beneficial effect on the sensory threshold. Two main results came out from the present work, respectively related to the proposed task's unisensory and multisensory conditions.

In terms of unisensory processing, we found that visual information, alone or combined with auditory, tactile, or audio-tactile stimuli, dominates perception. This finding is in line with previous works demonstrating the higher reliability of vision in perceiving simultaneous stimuli (Foulke, 1982; Merabet and Pascual-Leone, 2010; Pasqualotto et al., 2013; Thinus-Blanc and Gaunet, 1997). Research has also underlined that the combination of perceptual experiences from the environment and visual experience drives the development of allocentric spatial skills (Nardini et al., 2009; Vasilyeva and Lourenco, 2012). Moreover, spatial accuracy and precision of an event improve when multiple senses, congruent in space and in time, are integrated (Gori, 2015). However, our findings showed that when the stimulated area increases, a delayed responsiveness can be observed in the visual domain, indicating that size of stimulation has an effect in terms or visual responsiveness. A possible explanation might be that, when stimulation is conveyed on the body the faster response of touch is due to the fact that touch contributes to represent space based on egocentric (bodily) coordinates. Concerning hearing, we found that auditory responsiveness was not affected by the size of the stimulated area but auditory accuracy did not improve along with the increase of stimulated area, and this might be due to less reliability of auditory than visual information based on external landmarks, and than tactile information on the body. Several studies have demonstrated that vision typically dominates other sensory modalities in perception, producing a strong bias in case of conflicting events (Alais and Burr, 2004; Anderson and Zahorik, 2011; Bertelson and Aschersleben, 2003; Botvinick and Cohen, 1998; Flanagan and Beltzner, 2000; Zahorik, 2001). Our result might suggest that increasing the surface area on the body produced a sensory conflict between multiple sensory modalities, independently of the spatial and temporal coherence of stimulation.

Consequently, we might argue that conflicting events are solved by vision under a more cognitive point of view, while auditory and tactile stimuli foster perceptual abilities when multiple and proximal stimuli add up in space. A further explanation of the late responsiveness of vision in the task proposed might be related to the coexistence of retinotopic and spatiotopic reference frames to build spatial maps of the environment (Gardner et al., 2008; Golomb et al., 2008; Macaluso and Maravita, 2010; Wandell et al., 2007). Since retinotopic coordinates can induce an error signal when the fovea has to be moved and kept on a selected target, such a reference system can be considered more viewer-centered than spatiotopic frames of reference, which determine observer-independent properties of stimuli (Noory et al., 2015). According to this view, we might conclude that retinotopic and spatiotopic reference frames get into a conflict when perceptual features are processed, producing a significant delay in responsiveness, while spatiotopic coordinates overcome when cognitive processes take place and guide the other senses in encoding bodily space.

In terms of multisensory processing, we found that audio-tactile interaction enhances sensory accuracy more than unisensory (audio, tactile) processing only when the stimulated area increases. Indeed our results indicate that a significant increase in sensory accuracy is evident only when the surface areas correspond to four devices (25 cm^2), suggesting that the dimension of stimulated area might facilitate multisensory interaction. A possible reason for this is that, while vision dominates the spatial representation, a cost on integrating bigger spatial and tactile areas might emerge. When vision is not available, the association between auditory and tactile stimuli might have a stronger benefit for a bigger area of stimulation, where unisensory uncertainty is smaller. This idea might be supported by previous findings on the computation of frequency that showed a convergence between auditory and tactile stimuli in the case of spatiotemporal coherence (Foxe, 2009). According to such a view, other works have highlighted the early convergence and integration of auditory and tactile inputs at sensory cortices level (Brandwein et al., 2011; Finocchietti et al., 2015b; Foxe et al., 2002, 2000; Keniston et al., 2010; Meredith et al., 2009; Schroeder et al., 2001).

Overall, this work aimed to unravel the role of vision combined with audition and touch in space representation in an increasing bodily area. Our results suggested that, since multisensory interaction is driven by vision improved response accuracy with the increasing of stimulated area, vision provides a more reliable spatila information to encode peripersonal space. This result supports the idea that vision enhance spatial change discrimination when multiple stimuli occur in the same location and time. On the other hand, relying on visual cues might affect responsiveness to stimulation. Depending on vision seems to have a cost in terms of the spatial perception of both unisensory and multisensory events, while touch might guide audition in the discrimination of an increasing audio-tactile area on the body. Indeed, the combination of audition and touch improved the performance compared to unimodal auditory stimuli for a high number of active units, which might highlight a leading role of touch, based on body-centered spatial coordinates, in audio-tactile interaction process.

Concerning the TechARM system's validation, results confirmed its effectiveness in conveying unisensory and multisensory spatial stimuli. Moreover, thanks to the system's performing features, we implemented a novel paradigm, investigating whether the size of the stimulated area can effectively improve accuracy in the discrimination of spatial stimuli (i.e., spatial summation effect). With the present study, we demonstrated that vision drives multisensory integration of different sensory modalities with increasing stimulated area, with a detrimental effect in terms of responsiveness to stimulation. Moreover, the combination of auditory and tactile stimuli increased along with the stimulated area. These findings better define the interaction between sensory modalities and spatial area, highlighting the importance of assessing and training multisensory spatial skills in case of visual disability.

3.3.2 Assessment of spatiotemporal interceptive skills in interactive scenarios

The present study has been performed to assess the efficacy of the Tech-ARM in providing static and dynamic stimulation on the body, creating the impression of fixed or moving targets and recording users' responses in real-time. Indeed, it has been shown that it is possible to localize and intercept a moving object with visual feedback and rely on other senses such as touch and hearing. Nonetheless, no study has directly compared interception accuracy across senses (vision, touch, hearing) on the body. The validation of a device that permits to measure the interception accuracy in unisensory and multisensory conditions quantitatively and directly on the body would comprehensively assess spatial and temporal aspects.

Impairments in the typical functioning of a sensory modality, such as problems related to vision, can affect the development of spatial and locomotor competencies, interpretation and integration of input from other senses, cognitive and social skills (Hyvärinen, 1995). Although it is generally assumed that increased auditory and tactile skills may compensate for a visual deficit, it was demonstrated that vision impairments could also negatively affect the development of other sensory modalities (Gori et al., 2014). To date, the use of innovative systems for the quantitative assessment of sensory stimulation responses is increasing, particularly to evaluate the development of spatial coding skills (Colenbrander, 2010).

In the present study, we investigated perceptive mechanisms (e.g., unimodal and multimodal perception) of spatial representation by focusing on interception (see Schiatti et al., 2020). Interception is a fundamental ability in daily activities that require consolidated spatiotemporal skills, since it is based on predicting and integrating an individual's movement and the movement of the object to be intercepted to produce a timed motor response (Brenner and Smeets, 2018). While most of the research related to interception has mainly focused on the role of vision in guiding motor actions to reach an object (Port et al., 1997), it has been recently shown that it is possible to localize and intercept a moving object even relying on other senses such as touch and hearing. For instance, intercepting a tactile target can be compared to visual targets' interception, depending on haptic judgments on the position and velocity of the moving stimulus (Nelson et al., 2019). Similarly, sounds seem to provide prospective information for the purposeful control of goal-directed behavior. Specifically, individuals can vary the velocity profile of their intercepting movements based on the moving sound object (Komeilipoor et al., 2015; Shaffer et al., 2013). Despite the relevance of understanding such perceptual mechanisms, extensive data assessing a direct comparison of interception accuracy across senses (vision, touch, hearing) on the body are still missing to date. The present study's main aim was to validate the TechARM (see Chapter 3, Section 3.2.1) by using a manual interception task performed on a group of sighted adult subjects. The task consisted in the delivery of visual, auditory and tactile stimuli, either static or moving across the subject's arm, and in the direct record of users' responses, without the need of complex equipment, e.g. a motion tracking system.

Sample

Six sighted adults (average age: 27 ± 3.28) took part in both experiments after giving their written consent with the experimental procedure, approved by the local Ethics Committee (Comitato Etico ASL3 Genovese).

The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.18 (Cohen's d = 1.09);
- α err. prob. = 0.05;
- power (1-β err. prob.) = 0.95.

Task and procedure

The experimental protocol was splitted in: i) Position task; ii) Interception task (see Figure 3.14). The protocol for both tasks followed the guidelines presented in the related literature (Nelson et al., 2019). Participants sat with their hands laying on a table, with six TechARM

Figure 3.14 Experimental setup for the TechARM system validation.
(a) The starting position at the beginning of the experimental session. **(b)** Position and **(c)** Interception **(c)** tasks protocols.

units placed in a row on their left/ right arm (right-handed/ left-handed). They were asked to perform a tapping task, with the goal of matching the position of a static stimulus on their arm (Position), or intercepting it while it was moving along the arm (Interception). The stimuli, either static or moving, were delivered by the TechARM units in the visual (V), tactile (T), and auditory (A) modalities, in the form of white LED lighting, vibration, and a white noise sound, respectively. Each trial started with the subjects placing their dominant-hand index finger at a starting point indicated on the table (see Figure 3.14a). After a beep, the stimulation started and the subject was instructed to match the position of the stimulus as fast as possible by tapping the upper sensitized surface (embedded with the capacitive sensor) of the active TechARM unit.

Position task

The task took into account individual baseline differences in position detection accuracy for stimuli of different sensory modalities (see Figure 3.14b). This allowed us to include such differences when interpreting the interception task results. Six TechARM units covered a distance of 15 cm (2.5 cm per unit) on the participant's forearm. During the trial, one out of the six units delivered a 200ms stimulation in one of the three sensory modalities, and participants had to tap the target as soon as they felt it. For each position on the arm, there were three repetitions per sensory modality, resulting in 54 trials.

Interception task

During this task, the TechARM units were programmed to deliver a certain stimulation (either V, T or A), with a progressive delay from an end of the row to the opposite one, thus simulating a moving stimulus (see Figure 3.14c). Participants were instructed to intercept the stimulus by tapping on the active unit as fast as possible after the trial started. Three stimuli durations were implemented, namely 100ms, 200ms, and 300ms, leading to an apparent speed of approximately 25cm/s (high), 12.5cm/s (medium) and 8.3cm/s (low), respectively. The starting positions always corresponded to the two extremities of the row. Therefore, the stimulus could travel in the elbow-to-wrist direction or the opposite way, resulting in a total of 18 conditions. For each condition, there were 5 repetitions, leading to a total of 90 trials per participant.

Data analysis and statistics

Position task

The performance was evaluated in terms of Response Time (RT), calculated as the temporal interval between the start of the trial and the first touch detected, and Position Error (Errp), calculated as the distance between the selected unit and the active unit. We assessed that data did not follow a normal distribution (Shapiro-Wilk test), and we applied paired permutation t-tests with Bonferroni correction for multiple comparisons (significant value: $\alpha = .05$).

Interception task

The performance was evaluated in terms of Response Time (RT), and Time Error (Errt),calculated as the temporal interval between the tap and the time in which the selected unit was active (Errt > 0 if the unit was tapped after the end of its activation time, Errt < 0 if tapped before its activation time, Errt = 0 if tapping matched time of unit's activation). We assessed that data did not follow a normal distribution (Shapiro-Wilk test), and we applied paired a permuted two-way ANOVA analysis with "RT" and "Errt" as dependent variables, and "stimulus type" (three levels: V, A, T) and "speed" (three levels: Low, Medium, High) as within-subjects factors, with Bonferroni correction for multiple comparisons (significant value: $\alpha = .05$).

Results

Position task

We found that the ability to localize stimuli on the arm strongly depends on the sensory information provided (see Figure 3.15b) for what concerns static targets. Results suggest that participants tend to localize less accurately T compared to V stimuli (p = 1.92e-19), A compared to V stimuli (p = 5.48e-14) and T compared to A stimuli (p = 0.01). Therefore, participants seem to be overall more impaired in tactile localization of static stimuli on the arm. On the contrary, as shown in Figure 3.15a, no significant difference exists between audition and touch when considering reaction times (p = 0.26), while V significantly differs from T (p

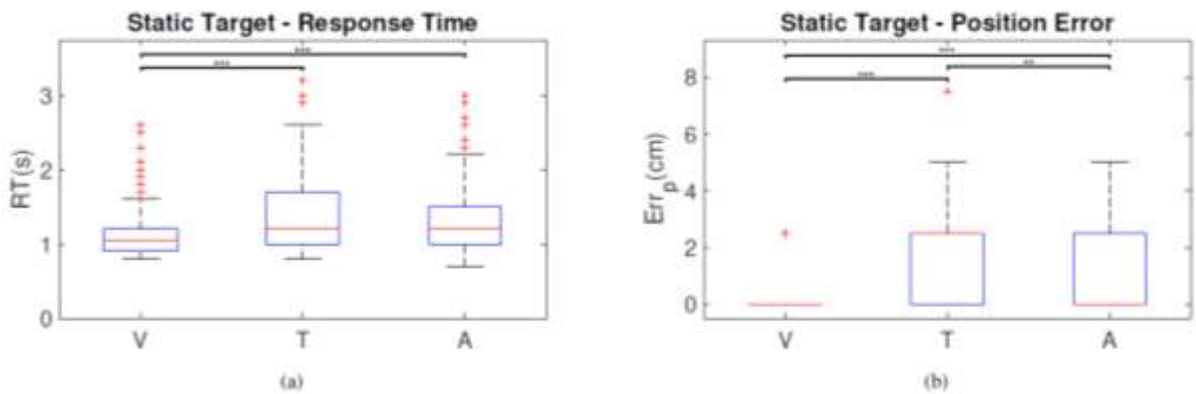

Figure 3.15 Position experiment results (distributions among subjects).
Results in terms of response time RT (a) and Position Error Errp (b), comparing V, T and A conditions. Each box indicates the distribution median (red line), the 25th and 75th percentiles, and outliers ('+'). Stars highlight significant differences between conditions according to paired permutation t-tests (*$p \leq 0.05$, **$p \leq$ 1e-2, ***$p \leq$ 1e-3).

= 4.00e-6) and A (p = 4.27e-4). Overall, results suggest that the visual modality leads to faster and more precise responses.

Interception task

For what concerns dynamic targets, revealed for both RT and Errt a significant effect of stimulus type (p < 2.20e-16) and speed (p < 2.20e-16), as well as of their interaction (p = 1.00e -3). For V and T, RT decreased with increasing stimulus velocity (see Figure 3.16a). This confirms previous literature findings on tactile and visual interception (Nelson et al., 2019), and supports the idea that our device is suitable for investigating perception. Results from Errt (Figure 3.16b) indicate that also interception accuracy varied depending on stimulus velocity. Indeed, while participants correctly intercepted the moving stimulus across all sensory conditions for medium velocity (200ms), they manifest a motor delay resulting in a positive temporal error for high velocity (100ms) and motor anticipation resulting in a negative temporal error for low-velocity stimuli (300ms) in case of acoustic stimuli. This can be intercept auditory targets more quickly when fast compared to slow stimuli are presented (Komeilipoor et al., 2015).

Another interesting result comes from the observation that, while all sensory modalities show the same interception accuracy for a medium stimulus velocity, V modality behaves similarly to T and better than A for slow targets, and similarly to A and better than T for fast targets. Overall, findings from our study suggest that auditory and tactile information might be effective in compensating and eventually substituting visual inputs to develop interception capabilities on the body.

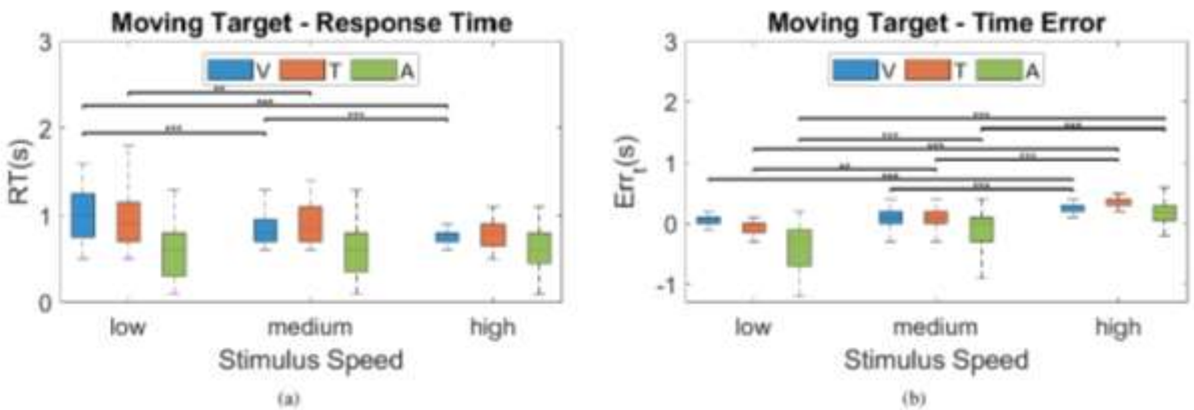

Figure 3.16 Interception experiment results (distributions among subjects).
Results in terms of response time RT (a) and Time Error Errt (b), for low, medium and high speed of moving target, comparing V, T and A conditions. Outliers are not shown. Stars highlight significant differences between conditions according to paired permutation t-tests (*$p \leq 0.05$, **$p \leq$ 1e-2, ***$p \leq$ 1e-3).

Discussion

In the present study, we presented a novel wearable system called TechARM, suitable to be used in investigating perceptive capabilities during interactive tasks, e.g., the interception of a moving target. When static stimuli were provided, the visual modality drove participants to faster and more precise performance. This can be explained by taking into consideration the spatial and temporal resolution of the visual system, being dependent on the resolution of the fovea (Danilova and Bondarko, 2007). On the other hand, individuals similarly react to auditory and tactile stimulations in terms of velocity, but they better identify the location of the stimulation when using the auditory modality. Such observation could be explained both by the type of stimulus, i.e. a vibration transmitted through the whole TechARM unit bottom surface, and by the resolution of skin receptors on the arm (Cholewiak et al., 2004). In the case of dynamic targets, the decrease of RT when visual and tactile stimuli were provided confirms previous literature findings on tactile and visual interception (Nelson et al., 2019), and supports the idea that the TechARM system might be suitable for investigating spatial perception.
Moreover, while participants correctly intercepted the moving stimulus across all sensory conditions for medium velocity (200ms), they manifest a motor delay resulting in a positive temporal error for high velocity (100ms) and a motor anticipation resulting in a negative temporal error for low-velocity stimuli (300ms) only in case of auditory stimuli. This can be interpreted in the context of the existing literature on the topic, showing that individuals intercept auditory targets more quickly when fast rather than slow stimuli are presented (Komeilipoor et al., 2015).

Another interesting result comes from the observation that, while all sensory modalities show the same interception accuracy for a medium stimulus velocity, the visual modality behaves similarly to tactile and better than auditory modality for slow targets, and similarly to auditory and better than tactile modality for fast targets. This suggests that multisensory audio-tactile feedback might improve individuals' interception abilities by providing more robust information than with unimodal feedback.

Concerning the validation of the TechARM system, results confirmed its effectiveness in reproducing findings of previous works in the field. Moreover, thanks to the system's performing features, we implemented a novel paradigm, comparing interception accuracy across visual, auditory and tactile sensory modalities. With the present study, we demonstrated that auditory and tactile information, other than vision, can be used to intercept a target on the arm and that the velocity of dynamic stimuli strongly affects interception accuracy. These findings shed light on the role of predictive abilities in motor action planning. Therefore, they highlight the importance of assessing and improving interception skills in case of sensory disabilities, such as blindness.

3.3.3 Effects of body-centered training on auditory spatial competencies in adults with temporal visual deprivation

The present study has been performed to investigate whether ABBI would be a reliable tool to improve spatial skills in the temporary or permanent absence of vision. Specifically, we tested the effects of audio-motor training performed with ABBI on recognizing auditory shapes in sighted adults (Section 2.1). Indeed, it has been shown that audio-motor coupling can improve sensory accuracy in specific auditory and proprioceptive tasks in both children (Cappagli et al., 2019, 2017) and adults (Finocchietti et al., 2017) with visual impairment. Nonetheless, no study has investigated whether more complex perceptual tasks, such as shape recognition, might improve after a training reinforcing audio-motor association. The validation of a device that enhances spatial perception by producing audio-motor correspondences would have important implication in terms of rehabilitation outcomes for children with a visual disability.

The development of Sensory Substitution Devices (SSDs) to transform visual stimuli into auditory or tactile information (Bach-y-Rita and Kercel, 2003; Gori et al., 2016; Meijer, 1992; Proulx and Harder, 2008) has reinforced the assumption that audition can substitute vision in the recognition of visual properties of an object, e.g. the shape (Amedi et al., 2007; Bizley and Cohen, 2013; Boyer et al., 2015; Carello et al., 1998). Furthermore, recent studies have demonstrated that the association of auditory feedback to bodily movements can be beneficial for spatial perception (Aggius-Vella et al., 2020; Cappagli et al., 2019, 2017; Finocchietti et al., 2017). Therefore, audition can be informative in providing real-time feedback about motor performance by explicit and implicit sensorimotor learning (Bevilacqua et al., 2016; Schaffert et al., 2019; Scholz et al., 2014), which is considered a crucial factor for spatial perception. Nonetheless, no study to date has assessed whether auditory feedback coupled with motor information would enhance the ability to discriminate a specific spatial property, i.e. objects’ shape, presented as spatialized sounds. Moreover, it is not clear whether training the recognition of auditory shapes through audio-motor feedback would produce an automatic transfer of visual shape properties, such as the closure of contours. Indeed, according to the Gestalt principle of 'closure' (Wertheimer, 1923), the most relevant cue that allows the visual perception of an object is its closed contour.

In the present study, starting from the findings obtained in Chapter 2 (Section 2.4), we assessed whether blindfolded sighted adults improve their ability to recognize auditory shapes after an audio–motor training with the use of the ABBI devices included in the ABBI-K system (see Martolini et al., 2020). We hypothesized that the audio-motor training would produce more positive effects on recognizing auditory shapes compared to solely auditory training since it provided multimodal contingencies that are more effective than unimodal stimulation (Bahrick et al., 2004; Shams and Seitz, 2008). Secondly, to investigate whether such properties of visual perception, as closeness, would be automatically transferred to audition, we evaluated whether auditory feedback of body movements would influence the discrimination of open- versus closed-contour auditory shapes. Accordingly, we presented two untrained open and two untrained closed shapes conveyed through auditory stimuli to be recognized, and we expected that the training would allow a generalization to both untrained open and untrained closed shapes in the auditory domain. Finally, we assumed that well-performed audio–motor training would help sighted adults with temporal deprivation of visual inputs to improve the recognition of auditory shapes, regardless of the contour (open, close).

Sample

The same twenty-two sighted volunteers of the work presented in Chapter 2, Section 2.4 participated in this study. Eleven adults (age range: 19–38 years, mean age: 26.9 ± 6.36 years, seven females) were assigned to the first group (experimental group), while 11 adults (age range: 20–29 years, mean age: 24.5 ± 2.73 years, six females) were assigned to the second group (control group). We recruited participants with the same procedure explained in Chapter 2, Section 2.4. Before starting the experiment, written consent to the experimental protocol was provided by each participant, as required by the Declaration of Helsinki and the local Ethics Committee (Comitato Etico ASL3 Genovese). The sample size was calculated with the free software G*Power 3.1 (www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/), based on the following parameters:

- effect size dz: 1.25 (Cohen's d = 1.30; see Carello et al., 1998);

- α err. prob. = 0.05;
- power (1-β err. prob.) = 0.95.

Task and procedure

As explained in Chapter 2, Section 2.4, participants entered the experimental room blindfolded to prevent them from seeing the setup. The experiment was divided into three consecutive sessions: (1) the pre-training session, during which participants performed the auditory shape recognition task for the first time (the experimental session in Chapter 2, Section 2.4); (2) the training session, during which participants performed audio–motor (experimental group) or a completely passive auditory training (control group) for 30 min; (3) the post-training session, during which all participants performed the auditory shape recognition task for the second time. The whole experiment was performed on the same day and lasted about 1 h and 30 min. Preliminarily to the pre-training session, participants were allowed to familiarize themselves with a tactile version of the four shapes (diamond, house, staircase, spiral) presented in the auditory shape recognition task (see Chapter 2, Section 2.4). The auditory shape recognition task was administered to both groups of participants and consisted of the verbal recognition of four semantic shapes (diamond, house, staircase, spiral) presented as continuous sounds. The experimental setup and procedure of the task were the same as the study presented in Chapter 2, Section 2.4.

The training

The training lasted about 30 min for both groups (experimental and control) and required participants to understand how a shape could be perceived through hearing while blindfolded until they sat in front of the experimenter behind the setup. The experimental group performed active training based on the association of auditory and motor information from their body movements. Participants were required to wear a sound source on the wrist corresponding to the dominant hand and reproduce the same simple arm movements previously performed by the experimenter, who wore a sound source on both wrists (Figure 3.17). The auditory source used for the training was ABBI, the wearable device included in the ABBI-K system, that has been previously adopted to enhance spatial perception in visually impaired people (Cappagli et al., 2019, 2017).

The training's goal was to make participants conscious of the position of sounds in peripersonal space by relying on body-centered coordinates. The sound produced was an intermittent sound (pure tone) of 500 Hz and 180 bpm, as previously used in a study by

(Finocchietti et al., 2017, 2015b). The training consisted of two sessions, with increasing difficulty. During the first session, participants were required to listen to one out of four simple auditory stimuli (horizontal line, vertical line, diagonal line, and curve line) and reproduce it. During the second session, participants were required to listen to one of four complex auditory stimuli (half triangle, half rhombus, half circle, and a half square) and reproduce it. Before starting each training session, participants took the blindfold off while the experimenter in front of them showed the first and second training sessions' shapes, respectively. After a short demo, participants were blindfolded again and the training started. On each training trial, the experimenter produced auditory stimuli by moving both arms sequentially (right and left in random order) to mimic the stimulus (simple or complex). Immediately following that, participants were asked to reproduce the auditory stimulus with both arms in sequence, one arm with only motor feedback (arm without ABBI) and the other arm with audio–motor feedback (arm with ABBI). In the first session of the active training, the four trajectories (horizontal line, vertical line, diagonal line, and curve line) were reproduced with both hands 10 times each, for 40 trials with the left hand and 40 trials with the right hand (total: 80 trials). Since the difficulty of the training increased, we reduced the number of repetitions in the second session. Each participant reproduced the four half shapes (half triangle, half rhombus, half circle, and a half square) with both hands five times each, for 20 trials with the left hand and shapes (e.g., diagonal line, half rhombus for diamond), presented in the experimental sessions before and after the training. We supposed that this kind of training would improve the ability to discriminate shapes with different features, such as curves or vertical lines, similarly to 20 trials with the right hand (total: 40 trials). Overall, the training was intended as a practice session based on recognizing parts of open (e.g., curve line, half circle for shell) and closed image representation paradigms (Bai et al., 2014). Concerning the passive auditory training, the control group performed the same number of trials per session and verbally named each trajectory or half shape without reproducing them. No feedback was given to participants during either the active or the passive trainings. For this reason, in the audio–motor training participants were not expected to repeat the movement for incorrect reproduction trials. If participants reported being unsure about the experimenter's performance, they were allowed to hear the trials for a second time.

Data analysis and statistics

For each participant, we calculated an index of correctness given as the number of correct responses for each auditory shape divided by the total number of trials for each shape (e.g., five correct responses for the shell gave an index of the correctness of 0.5). The correctness index was calculated for the pre-training (see 'recognition score' in Chapter 2, Section 2.4) and the post-training sessions. We focused on each participant's improvement (Δ) across the test phases (pre-training and post-training), expressed as an index between 0 and 1. Concerning the training, we collected the score obtained by each participant for each level of difficulty (number

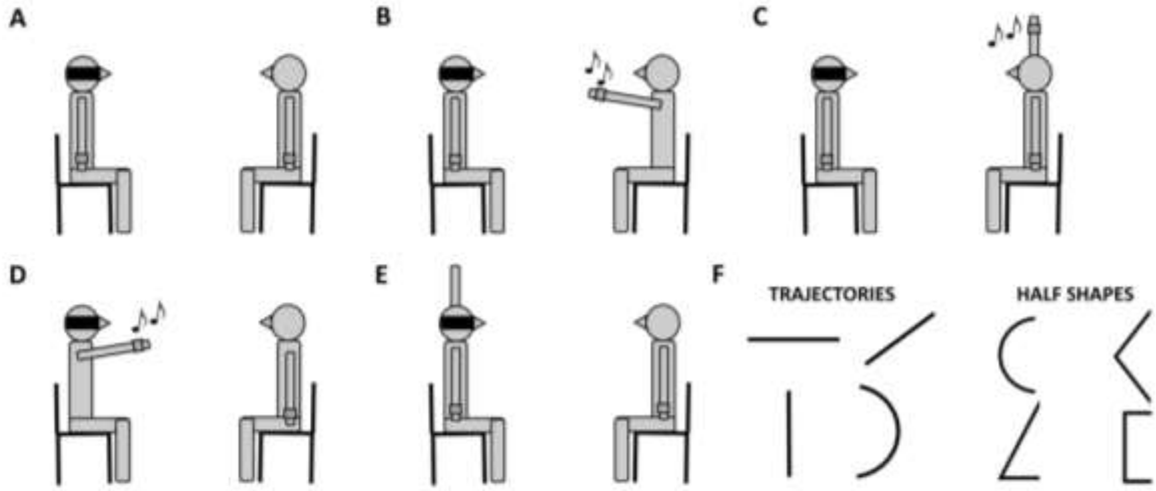

Figure 3.17 Active audio–motor training of the auditory shape recognition task.
Participants of the experimental group undergo an active training based on the association of auditory and motor information from their own body. **(A)** The blindfolded participant (left) and the experimenter (right) sit in front of each other. The experimenter wears an Audio Bracelet for Blind Interaction (ABBI) device on both wrists, while the participant wears an ABBI device only on his dominant wrist. **(B, C)** The experimenter produces auditory shapes with ABBI (both left and right hemi-spaces in random order). **(D, E)** The participant is asked to reproduce with both arms the auditory shapes performed by the experimenter. **(F)** Sessions of training. During the first session (difficulty level 1), four simple trajectories (horizontal line, vertical line, diagonal line, and curved line) are presented, while during the second session (difficulty level 2), four complex auditory shapes (half triangle, half rhombus, half circle and half square) are presented.

of correct responses, normalized between 0 and 1). The final score index was averaged on the total number of trials of the two training sessions. We verified that data were normally distributed, performing the Shapiro–Wilk test of normality using the free software R (Free Software Foundation, Boston, MA, USA). We conducted three separate mixed ANOVAs with 'pre-training score', 'post-training score' and 'improvement' as dependent variables, with 'training groups' as between-factor variable (two levels: Experimental, Control) depending on the kind of training performed, and 'shapes contours' as within-factor (two levels: Open, Closed). Bonferroni correction was applied in case of significant effects to adjust the p-value of multiple comparisons (significant value: $\alpha = .05$).

Furthermore, we evaluated whether there was a relation between the score obtained during the training and the improvement in auditory shapes recognition. We calculated the median value of training scores among the participants of each group. We divided participants into two subgroups: ‘Good training’ if the score value was greater than the median, ‘Bad training’ otherwise. We analyzed whether the improvement was influenced by the test score, comparing the experimental to the control group with a one-tailed t-test (significant value: $\alpha = .05$).

Results

Since no significant difference was observed between the experimental and control groups in the recognition of auditory shapes during the pre- ($F_{(1, 20)} = 0.29$, $p = 0.59$) and post-training ($F_{(1, 20)} = 1.24$, $p = 0.28$) phase, all participants were collapsed in a single group. Participants were better at recognizing open- than closed-contour shapes (main effect: contour shapes; pre-training: $F_{(1, 20)} = 7.24$, $p = 0.014$, Bonferroni: p = 0.005; post-training: $F_{(1, 20)} = 10.61$, $p = 0.004$, Bonferroni: $p = 0.0007$), regardless of the type of training performed (interaction training groups × contour shapes; pre-training: $F_{(1, 20)} = 0.27$, $p = 0.61$; post-training: $F_{(1, 20)} = 0.59$, $p = 0.45$).

We then evaluated the improvement of participants in the auditory shapes recognition task after both training (Figure 3.18). Results suggested that performing active or passive training influenced the improvement in the recognition of auditory shapes with open or closed contours (interaction training groups × contour shapes; $F_{(1, 20)} = 6.86$, $p = 0.016$)]. The recognition of open shapes was significantly higher than that of closed shapes within the experimental group (Bonferroni: $p = 0.015$). Moreover, participants who underwent the audio–motor training improved their performance more than participants performing the passive training, specifically in the recognition of open shapes (Bonferroni: $p = 0.045$). This result confirmed our hypothesis on the effectiveness of active training based on the reproduction of movements combined with sounds in the recognition of auditory shapes.

Finally, we analyzed the improvement obtained by experimental and control groups in the recognition of open versus closed shapes, taking into account participants' score during the training. Figure 3.19 shows that only those who collected a high score during the active training significantly improved their abilities in recognizing open shapes, concerning participants who did a good passive training ($t_{18} = 2.21$; $p = 0.021$). In the case of a low score, both experimental and control groups showed no significant difference in recognizing open shapes ($t_{22} = 1.06$; p

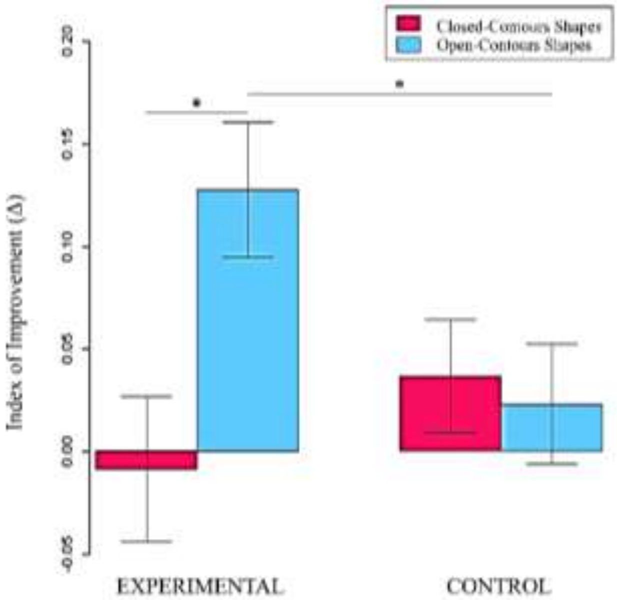

Figure 3.18 Improvement in the auditory shape recognition task after the training.
The experimental group, whose members do the active audio–motor training based on the coupling of auditory and motor feedback, improves the recognition of open shapes significantly more than the control group (between factor, $p < 0.05$), who undergoes a passive training relying solely on the auditory information produced by the experimenter. Moreover, within the experimental group, open-contour shapes are perceived significantly better than closed-contour shapes ($p < 0.05$).

= 0.30). Concerning closed shapes, no significant differences were reported between experimental and control groups with both high ($t_{18} = 0.00$; $p = 1.00$) and low score ($t_{22} = -1.52$; $p = 0.14$). In this case, our hypothesis regarding an improvement in the recognition of auditory

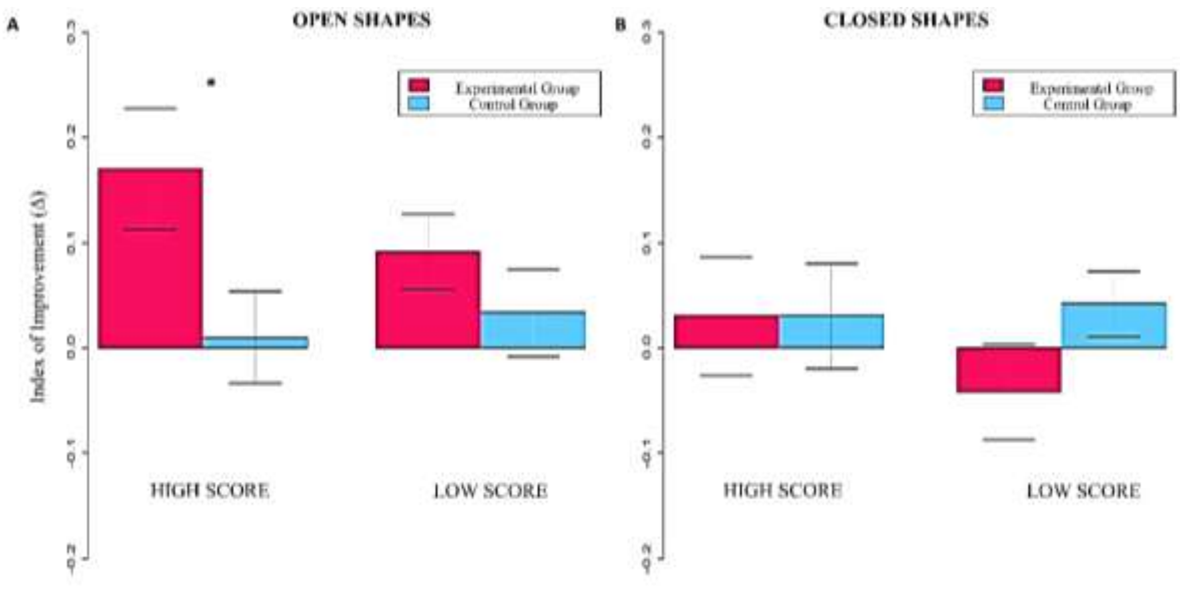

Figure 3.19 Comparison between the improvement obtained by the experimental and control groups in case of high or low score during the training.
(A) When scoring high at training, participants of the experimental group improve more than those of the control group in the recognition of open-contour shapes ($p < 0.05$). When scoring low, no significant difference is observed between the two groups ($p = 0.30$). **(B)** No significant difference is observed between the two groups when scoring both high and low towards closed-contour shape recognition ($p > 0.10$).

open and closed shapes due to audio–motor training was confirmed only in the case of open shapes.

Overall, the results demonstrated that doing good training based on the coupling of auditory and motor feedback improves the recognition of open shapes conveyed through sounds, shifting from the body to external references.

Discussion

Recent studies have shown that auditory feedback associated with body movements could enhance spatial representation both in sighted (Aggius-Vella et al., 2020) and blind individuals (Cappagli et al., 2019, 2017; Finocchietti et al., 2017). In the present work, we hypothesized and demonstrated that coupling auditory cues with body movements could also improve the ability to recognize auditory shapes. Our findings showed that an active audio–motor training performed with ABBI (Finocchietti et al., 2015c; Porquis et al., 2017), a wearable device included in the ABBI-K system (Martolini et al., 2020a), and based on the reproduction of movements combined with sounds was effective in improving the recognition of complex shapes presented as auditory stimuli. Moreover, the higher the score during the training, the higher the improvement obtained in the recognition of open-contour auditory shapes. According to our results, providing a sound as a real-time feedback about movements can both explicitly and implicitly enhance sensorimotor abilities (Bevilacqua et al., 2016), while audition applied to motor performance seemed to be effective for rehabilitation and sport training (Schaffert et al., 2019; Scholz et al., 2014). In a work by Boyer and colleagues (2015), solely auditory cues provided information about the curvature of shapes in the absence of visual feedback, further confirming that audition can be successfully applied for spatial learning tasks. A growing body of research has demonstrated that audition employed to substitute but not to compensate vision can also help individuals to perceive typically visual features of objects via artificial soundscapes (SSDs - Sensory Substitution Devices; (Amedi et al., 2007; Bach-y-Rita and Kercel, 2003; Gori et al., 2016; Meijer, 1992; Proulx and Harder, 2008)). Nonetheless, the use of visual-to-auditory SSDs was effective only after long training, divided into multiple sessions lasting from 2 hours to 50 hours (Amedi et al., 2007; Striem-Amit et al., 2012b), while the audio–motor training proposed in this study lasted 30 min in a unique session and seemed to be effective as well.

Our work's first finding indicates that blindfolded sighted adults could improve the recognition of open-contour auditory shapes thanks to the coupling of auditory and motor feedback of their own body movements during a short training. This result is in line with our previous studies, showing that spatial perception can be enhanced by audio–motor training, especially in rehabilitation contexts of visually impaired individuals (Cappagli et al., 2019, 2017; Finocchietti et al., 2017). A possible explanation of such a result is that the association of auditory feedback with body movements might create a 'bridge' between body representation and external representation. In other words, audio–motor training could be used to shift the spatial representation from egocentric to external reference frames. This process, usually mediated by vision, can be guided by hearing through the sonorous feedback deriving from body-centered coordinates, allowing recalibration of the extra-personal space in allocentric coordinates.

Interestingly, the second finding of the present work shows that the audio-motor training was beneficial only to recognize open-contour shapes. Generally, this might indicate that the audio–motor training proposed might led to generalization to, at least, novel untrained open-contour shapes, while closed shapes need to be trained differently. Alternatively, in our study auditory feedback was used as real-time movement sonification. Therefore only implicit learning was possible. Nonetheless, it has been suggested that the combination of both explicit and implicit learning mechanisms can further improve perceptual performance (Bevilacqua et al., 2016).

Consequently, the auditory feedback as an alarm for movement errors might have also been used to signal shape reproduction errors in the training phase. Another possible explanation is that training based on audition better recalibrates the perception of open-contour shapes, which are less frequent in everyday life, while closed-contour shapes are more typical in the visual domain. Indeed, it is still possible that the property of closure is less predominant in auditory shape recognition compared to visual shape recognition, and therefore training benefits transfer from trained to untrained shapes.

Overall, this study's results suggest that auditory feedback associated with motor feedback deriving from body movements effectively conveys spatial information useful for auditory shape recognition. Furthermore, our findings may have important implications for rehabilitation outcomes, since they provide important inputs for the development of appropriate training procedures to be adopted in blindness, where auditory feedback associated with body movement might be essential to convey important spatial properties of objects.

3.3.4 Effects of audio-motor training on spatial representation in long-term late blind adults

The present study has been performed to investigate whether ABBI would be a reliable tool to assess and improve spatial representation in long-term late blind adults. Specifically, we tested the effects of audio-motor training performed with ABBI on auditory and proprioceptive competencies in long-term late blind adults. Indeed, it has been shown that audio-motor coupling can be an effective tool to train spatial skills in blind children, but no study to date has explored the effects of multisensory training on visually impaired adults.

Research has widely assessed that vision provides the most accurate spatial information, since it enables the representation of space based on the relations between objects in the environment, i.e. by relying on object-centered or allocentric frames of reference (Foley et al., 2015; Klatzky, 1998). Considering the importance of vision in giving the most accurate and reliable spatial information (Cappagli and Gori, 2019), the lack of visual experience may significantly compromise the development of other sensory modalities and, in general, the acquisition of spatial knowledge (Bigelow, 1996; Cattaneo et al., 2008; M. Gori, 2015; Koustriava and Papadopoulos, 2010; Ungar et al., 1995). It has been studied that visually impaired adults tend to adopt body-centered or egocentric frames of reference to encode space, based on the observer's perspective, with increasing difficulties in the use of an allocentric reference system (Iachini et al., 2014; Merabet and Pascual-Leone, 2010; Millar, 1994; Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997).

Further works have investigated how visually impaired individuals deal with the relation between sounds in space and time (Gori et al., 2014, 2010), finding a tendency to encode space based on temporal properties of auditory information (Gori et al., 2018). Specifically, early blind adults and late blind adults who spent more than 20 years without vision (i.e. long-term late blind) did not show the typical early activation of the occipital and temporal cortices, contralateral sound position in space, during the spatial bisection task (Campus et al., 2017). On the contrary, their occipital and temporal activation was influenced by the temporal instead of the sounds' spatial features (Amadeo et al., 2020; Gori et al., 2020b).

Although the recent introduction of Sensory Substitution Devices (Auvray and Myin, 2009; Bach-y-Rita and Kercel, 2003; Gori et al., 2016; Maidenbaum et al., 2014; Meijer, 1992; Proulx and Harder, 2008; Velázquez, 2010) has effectively helped blind individuals in processing visual stimuli (see Amedi et al., 2007), such technological systems are mainly intended as unimodal training aids, aiming at substituting sensory loss instead of reinforcing residual sensory abilities. The adoption of a multisensory approach to train visually impaired individuals has increased in importance (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008), since multisensory contingency can improve the detection of the amodal properties of events (Bahrick et al., 2004; Todd, 1912). For instance, it has been demonstrated that multisensory association of audition and motion is effective in enhancing sensorimotor learning and motor control in both sighted (Bevilacqua et al., 2016; Boyer et al., 2013) and visually impaired individuals (Cappagli et al., 2019, 2017; Finocchietti et al., 2017). In particular, the adoption of ABBI (Audio Bracelet for Blind Interaction; (Finocchietti et al., 2015c; Porquis et al., 2017)), a wearable auditory source activated by body movements included in the ABBI-K system (Martolini et al., 2018), in training activities of visually

Participant	Age	Pathology	Blindness duration (years)	Residual vision
#1	54	Nystagmus and retinitis pigmentosa	24	Lights and shadows
#2	47	Congenital glaucoma	41	No light perception
#3	59	Uveitis	48	No light perception

TABLE 3.1 Clinical details of long-term late blind participants (N = 3).

The table shows the chronological age at testing, pathology, and years of blindness duration (i.e. number of years spent without vision) for each participant.

impaired individuals improved their abilities in encoding space around them. Although it has been shown that a multimodal approach might be more effective than unimodal strategies to train spatial skills in blind children, to date no multisensory training has been effectively tested in blind adults. In particular, individuals who have experienced blindness for more than 20 years (long-term) might benefit from training involving residual sensory modalities to build a metric representation in the auditory domain based on spatial rather than temporal cues. Moreover, a further investigation on the effects of audio-motor training in long-term late blind adults on auditory and proprioceptive spatial abilities should be carried out.

In the present work, we assessed whether a training based on auditory feedback of body movements might improve spatial representation skills in long-term LB adults. Firstly, we hypothesized that audio-motor training would produce positive effects on long-term LB adults' auditory and proprioceptive spatial competencies. To test this hypothesis, we proposed a battery of spatial tasks before and after a training based on auditory and motor feedback coupling that lasted one month. The battery included: i) auditory transverse and frontal localization tasks, where participants indicated the final position of a moving sound source; ii) proprioceptive-motor tasks, where participants discriminated the ending point of arm movements.

Sample

Three participants with acquired blindness (i.e. late blind, LB) were recruited to take part in this study. Specifically, one participant (i.e., S01) was a female, aged X years old, who lost sight at X years old; another participant (i.e., S02) was a male, aged X years old, who lost sight at X years old; and the last participant (i.e., S03) was a male, aged X years old, who lost sight at X years old. For each participant, blindness duration (i.e., BD - the difference between chronological age at testing and age of blindness onset) was superior to 20 years. Clinical details of the three LB participants are summarized in Table 3.1. All of them reported normal hearing and no history of neurological, cognitive, or other sensory-motor deficits except for total blindness. The research protocol was approved by the ethics committee of the local health service (Comitato Etico, ASL3 Genovese, Italy) and conducted in line with the Declaration of Helsinki. Participants provided written informed consent prior to testing. Due to the actual pandemic caused by Covid-19, it was not possible to recruit more LB participants to be involved in the experimental protocol. For the same reason, we were not able to enroll control participants to increase the reliability of results due to the training in LB individuals.

Task and procedure

The procedure required LB participants to perform three experimental sessions: i) a pre-evaluative session (i.e., Pre-Session), involving a battery of behavioral tasks to evaluate spatial coding skills and an EEG recording to investigate neural correlates of complex spatial representations; 2) a training session (i.e. Training), during which participants performed spatial exercises based on auditory feedback associated with body movements; 3) a post-evaluative session (i.e., Post-Session), involving the same behavioral and EEG assessment proposed in Session 1 to test any improvement following the training. The Pre- and Post-sessions lasted 3 hours and were performed on two different days before and after the training, respectively. The Training session lasted 4 weeks and involved participants performing spatial exercises that consisted of reproducing upper-limb movements and paths. The whole training was based on auditory feedback of body movements provided by the wearable device ABBI (Audio Bracelet for Blind Interaction), which was clinically validated as rehabilitative technology to enhance spatial perception in visually impaired people (Cappagli et al., 2019, 2017; Finocchietti et al., 2015a).

The training

All the participants enrolled in the study performed the 4-weeks training based on the use of ABBI both with the experimenter and at home. Participants performed the audio-motor training with the experimenter for 1 hour once a week at IIT (4 hours over 4 weeks) and with a relative or alone at home for 1-3 hours per day (mean duration: 42 hours over 4 weeks), for an average total of 46 hours. During sessions both at IIT and at home, the sounds produced by ABBI were chosen by participants among pure tones (intermittent or continuous) at 500 Hz and 180 bpm (Finocchietti et al., 2017, 2015a), and preselected playback sounds stored in the device (e.g. waves, birds, drums) (Cappagli et al., 2019, 2017). The choice to use different kinds of sounds aimed to keep the participant involved and motivated during the entire training sessions. The spatial exercises were designed by readapting the protocol proposed by Cappagli and colleagues (2017), during which ABBI was worn on the wrist by either the participant or the experimenter/relative. Participants performed two types of training: a) static training, consisting in the localization of static sounds or the reproduction of moving sounds trajectories in peripersonal space with the upper limb while sat in front of the experimenter/relative; b) motor training, consisting in the localization of static sounds or the reproduction of auditory trajectories in extrapersonal space.

Below are listed the exercises of the static training:

- Localization of sounds in peripersonal space: the participant sat in front of the experimenter/relative, who wore ABBI on the wrist and moved the arm towards a position on either horizontal or vertical plan at different depth, with ABBI emitting a sound. The participant was asked to indicate the final position of the movement. If the response was wrong, firstly, the movement was reproduced by the participant holding the experimenter's hand, secondly, the participant repeated the task. The experimenter/relative always gave verbal feedback on response correctness. The main objective was to create a detailed auditory spatial map based on sensory-motor experience.
- Interception of sounds: the participant sat in front of the experimenter/relative, who wore ABBI on the wrist and moved the arm continuously along the horizontal/vertical plane,

with ABBI emitting a sound. The participant was asked to intercept the sound while moving. The main objective was to localize a moving sound source in peripersonal space.

- The lift: the participant sat in front of the experimenter/relative, who moved ABBI towards different positions along the vertical plane, with ABBI emitting a sound. The participant was asked to indicate at which height ABBI stopped emitting sounds. The main objective was to train sounds localization in the vertical plane.

The motor training comprised:

- Follow the sound: the participant stood at the starting position in front of the experimenter/relative, who wore ABBI on the wrist and moved randomly in the experimental/house room, with ABBI emitting a sound. The participant was requested to follow the sound and to stop when the sound stopped. The main objective was to enable participants to notice and consequently react to a moving sound source's directional changes in space.
- Localization of sounds in extrapersonal space: the participant stood at the starting position in front of the experimenter/relative, who wore ABBI on the wrist and moved towards a first random position in the experimental/house room, with ABBI emitting a sound. After stopping for 2 seconds, the experimenter/relative moved towards a second position, with ABBI still emitting the same sound, then stopped the sound after 2 seconds. The participant was requested to reach the final position by reproducing the same path. The path included straight, diagonal and curved lines. The main objective was to create an auditory spatial map based on sensory-motor training in far space.
- Mind the obstacles: the participant stood at the starting position in front of the experimenter/relative and was requested to reach a final position avoiding one or two obstacles (e.g. chairs) previously positioned in the experimental/house room. The game was structured into two levels of difficulty: 1) the experimenter/relative wore ABBI on the wrist and moved towards the final position, with ABBI emitting a sound. When standing in front of the obstacles, the experimenter/relative changed the path direction. The participant was requested to reproduce the path by remembering the position of obstacles and changing directions; 2) the experimenter/relative positioned ABBI on one obstacle, then turned ABBI on for 2 seconds. The participant was required to reach the obstacle,

- change direction and return to the starting position. The main objective was to create a mental spatial map based on the position of sounds in space.
- Reproduction of shapes in space: the participant stood at the starting position in front of the experimenter/relative, who wore ABBI on the wrist and moved in the experimental/house room representing a shape (e.g. circle, square, triangle) with coincident starting and ending points, with ABBI emitting a sound. The participant was requested to reproduce the same path. The main objective was to understand the shift from mental to the motor representation of geometrical shapes in space through sounds.

Besides the static and motor trainings, the participants were encouraged to use ABBI by wearing it on their wrists and doing common life actions, like setting the table or moving objects from a point to another inside a room. The main objective of body-centered (or egocentric) training was to improve spatial representation with object-centered (or allocentric) coordinates based on sensorimotor feedback.

Evaluation tasks

We developed a battery of spatial tasks to quantitatively measure sensorimotor training's effectiveness on spatial representation abilities of long-term LB individuals. The battery comprised the following four tasks:

- *Auditory transverse localization task*: participants sat in front of a paper grid positioned on a table opposite the experimenter. Six target points positioned at the same depth but opposite with respect to the central reference were indicated on the grid. The sound produced by the device ABBI was intermittent (pure tone) at 500 Hz and 180 bpm, as previously used in the experimental protocol of Finocchietti et al. (2015, 2017 (Finocchietti et al., 2017, 2015b)). During each trial, the experimenter moved ABBI emitting sounds towards one of the target points, and the sound stopped when the point was reached. The participant was asked to localize the final position of the moving sound. The number of repetitions per target point was 10, with a total amount of 60 trials. The task's goal was to localize the final position of a moving sound source on the horizontal plane.
- *Auditory frontal localization task*: the participant sat in front of a vertical grid opposite the experimenter. The setup was similar to that used by Finocchietti et al. (2017) in their experimental paradigm. Eight target points were positioned along the grid's four sides at the same distance with respect to the central reference. ABBI emitted an intermittent sound

at 500 Hz and 180 bpm (Finocchietti et al., 2017, 2015b). During each trial, the experimenter moved ABBI emitting sounds towards one of the target points, and the sound stopped when the target was reached. The participant was asked to localize the final position of the moving sound. The number of repetitions per target point was 5, with a total amount of 40 trials. The task's goal was to localize the final position of a moving sound source on the vertical plane.

- *Position matching task*: the participant sat centrally in front of a set of 16 loudspeakers, placed inside a metallic case with a sliding support and provided with a touch-sensitive surface (for further details, see Cuppone et al., 2018). The experimenter moved the participant’s dominant hand handling the sliding support from the starting position (center of loudspeaker 1) towards 6 target positions. After 1 second, the experimenter moved the hand back to the starting position. The participant was asked to replicate the same movement by ending in the perceived final position without a time constraint, and then the experimenter touched the loudspeaker surface on the correspondent point to register the matching position (Cuppone et al., 2018). The number of repetitions per target point was 5, with a total amount of 30 trials. A laptop controlled the speakers via MATLAB (R2018b, The MathWorks, USA). The goal of the task was to assess the proprioceptive motor skills of blind individuals.
- *Proprioceptive midline task*: the participant sat centrally in front of the same setup used in the *Position matching task.* The task was readapted from the protocol used by Pizzamiglio et al. (2000). The experimenter moved the participant’s dominant hand handling the sliding support from the starting position (center of loudspeaker 14) towards the center of 11 target positions: one central target point (loudspeaker 8), five on the left and five on the right concerning the central target. The participant was asked whether the hand was perceived on the left or the right with respect to his/her nose (body midline). The number of repetitions per target point was 5, with a total amount of 55 trials. The task's goal was to assess the influence of body midline on spatial judgments of blind individuals.

Data analysis and statistics

In the auditory transverse and frontal localization tasks, the accuracy error (relative error) was calculated as the difference (in mm) between the position reached by the participant and the target point along X- (accuracy-x) and Y- (accuracy-y) axes on the horizontal and vertical grids, respectively. As a measure of precision error (absolute error), we computed the Euclidean distance (in mm) between the end-point position reached by the participant and the target point. In the position matching task, we calculated the accuracy error as the difference (in mm) between the final position reached by the participant's hand and the center of the target loudspeaker along X-axis (accuracy). In the proprioceptive midline task, a binomial value (1 in case of correct response, 0 otherwise) was attributed to participants' verbal answers on the perception of their body midline with respect to their hand's final position. Statistical analyses were performed using R - Free Software Foundation, Boston, MA, United States. For all tasks, data did not follow a normal distribution (Shapiro-Wilk test of normality). On the contrary, data of auditory transverse and frontal localization tasks and data of the position matching task followed a gamma distribution (*gamma_test* function, R), while data of proprioceptive midline asks followed a binomial distribution. For each task, we applied a Generalized Linear Mixed Model (GLMM) fit by maximum likelihood (*glmer* function, R) with accuracy-x, accuracy-y, precision (auditory localization tasks), accuracy (position matching task) and correctness (proprioceptive midline task) as dependent variables, fixed-effect group "session" (two levels: Pre, Post), and random-effect group "subject" (total number: three).

Results

In the present thesis EEG data are not reported, since the Covid-19 global pandemic slowed down EEG data collection and analysis.

Auditory transverse localization task. The dependent variables accuracy-x, accuracy-y and precision resulted as gamma-distributed (accuracy-x: Pre: V = 2.28, $p = 0.11$; Post: V = -1.71, $p = 0.23$; accuracy-y: Pre: V = 0.43, $p = 0.76$; Post: V = -1.94, $p = 0.17$; precision: Pre: V = 1.36, $p = 0.33$; Post: V = 1.27, $p = 0.37$). As results showed, the training did not significantly improved auditory localization abilities in the horizontal plane, maintaining both accuracy errors (accuracy-x: $\chi^2 = 0.73$, df = 1, $p = 0.39$; accuracy-y: $\chi^2 = 0.85$, df = 1, $p = 0.36$) and precision error ($\chi^2 = 1.46$, df = 1, $p = 0.23$) within the same range (see Figure 3.20A,B,C).

Auditory frontal localization task. The dependent variables accuracy-x, accuracy-y and precision resulted as gamma-distributed (accuracy-x: Pre: V = -1.05, $p = 0.46$; Post: V = -2.71, $p = 0.052$; accuracy-y: Pre: V = -0.99, $p = 0.48$; Post: V = -2.54, $p = 0.072$; precision: Pre: V = -2.34, $p = 0.098$; Post: V = -0.61, $p = 0.67$). The training with ABBI helped participants to reduce the accuracy error along the X-axis ($\chi^2 = 13.20$, df = 1, $p = 0.00028$) (see Figure 3.20D), while no significant difference between the Pre- and Post-training sessions was shown along the Y-axis ($\chi^2 = 0.16$, df = 1, $p = 0.69$) (see Figure 3.20E). Concerning the precision error (Fig. 3.20F), participants showed a significant improvement in the localization of an auditory source on the vertical plane after the training ($\chi^2 = 39.85$, df = 1, $p = 2.74e\text{-}10$).

Position matching task. The dependent variable accuracy resulted as gamma-distributed (accuracy: Pre: V = -2.64, $p = 0.062$; Post: V = -2.71, $p = 0.052$). As shown in Figure 3.21, participants showed better proprioceptive spatial skills after the use of ABBI by reducing the accuracy error ($\chi^2 = 6.35$, df = 1, $p = 0.012$), increasing thus the capacity to match correctly the end-point of the hand movement.

Proprioceptive midline task. Results in this task suggested that participants correctly discriminated their body midline with no significant difference between Pre- and Post-training sessions ($\chi^2 = 0.070$, df = 1, $p = 0.69$).

Discussion

It has been widely demonstrated that vision leads the other senses in the developmental process of spatial representation (Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997; Vasilyeva and Lourenco, 2010). Indeed, when visual feedback is absent, blind people tend to substitute an object-centered (i.e., allocentric) perspective with body-centered (i.e., egocentric) frames of reference to build spatial maps of the environment, with increasing difficulties to rely on external auditory landmarks (Iachini et al., 2014; Merabet and Pascual-Leone, 2010; Millar, 1994; Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997).

In the present study, we hypothesized and assessed the efficacy of a one-month training with the wearable device ABBI (Finocchietti et al., 2015c; Porquis et al., 2017), based on auditory feedback of body movements, to enhance audio-proprioceptive spatial competencies in long-term (i.e., more than 20 years) late blind (LB) adults. Specifically, participants performed a battery of spatial tasks before and after the training, including auditory frontal and transverse localization tasks and proprioceptive-motor tasks. The spatial training protocol was readapted from Cappagli and colleagues (2017), and concerned static exercises, e.g. the localization of static sounds or the reproduction of moving sounds trajectories in peripersonal space with the upper limb, and motor exercises, e.g. the reaching of static sounds or the reproduction of auditory trajectories in extrapersonal space.

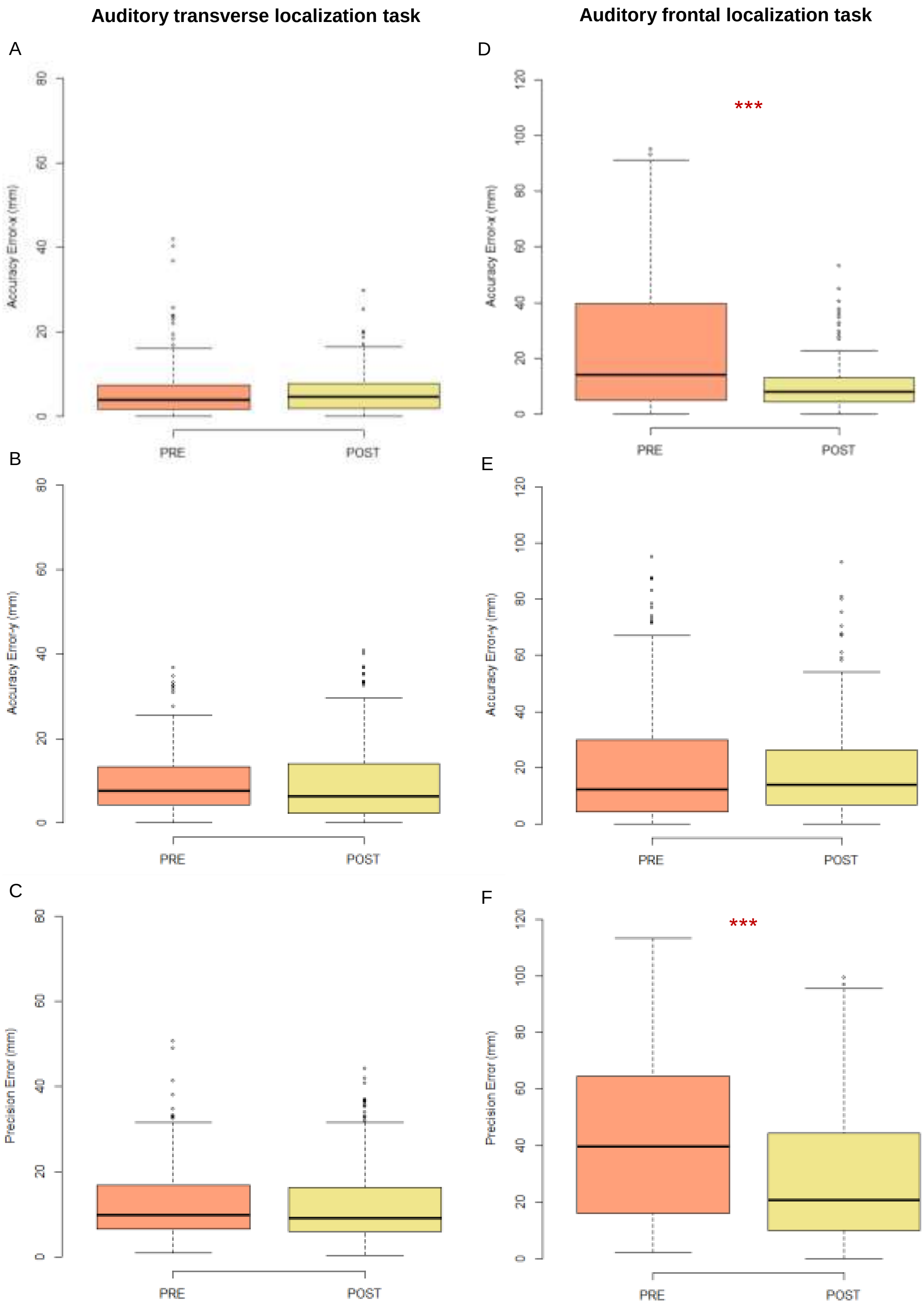

Figure 3.20 Results of long-term late blind adults in the auditory evaluation tasks. Concerning the auditory transverse localization task, the training seemed ineffective on the improvement of **(A)** accuracy error along X-axis ($p > 0.30$), **B)** accuracy error along Y-axis ($p > 0.30$) and **C)** precision error ($p > 0.20$). Concerning the auditory frontal localization task, **D)** the training with ABBI helped participants to reduce the accuracy error along the X-axis ($p < 0.001$), **E)** but not along the Y-axis ($p > 0.69$), and **F)** it significantly improved also the precision error ($p < 0.0001$).

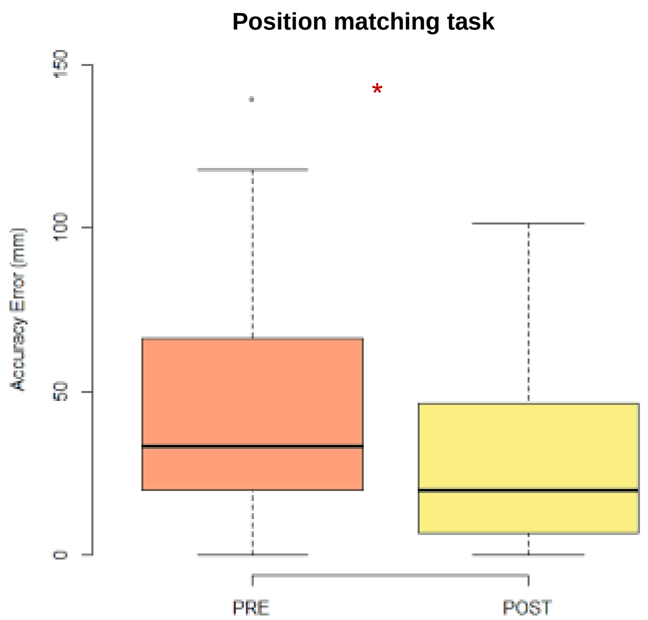

Figure 3.21 Results of long-term late blind adults in the proprioceptive evaluation task. Participants show a better performance the proprioceptive position matching task after the use of ABBI by significantly reducing the accuracy error ($p < 0.05$).

Concerning the purely auditory tasks, we found that participants did not show significant improvements in sound source localization on the horizontal plane along both spatial axes, maintaining the same accuracy and precision regardless of the training. In support of this result, it has been demonstrated that blind adults are skilled in the localization of static sounds in the horizontal plane (Doucet et al., 2005; Gougoux et al., 2004; King and Parsons, 1999; Lessard et al., 1998; Lewald, 2007; Roder et al., 1999), even at the cortical level, showing the recruitment of the visual cortex (Gougoux et al., 2005; Poirier et al., 2005; Renier and De Volder, 2005; Striem-Amit and Amedi, 2014; Weeks et al., 2000). Other studies suggest a superior performance of blind compared to blindfolded sighted individuals in case of sounds located in the horizontal plane (Abel et al., 2002; Tabry et al., 2013). Given all these statements, we might suppose that the training was ineffective due to high auditory abilities in the transversal plane. Conversely, the training fostered a significant improvement in the accuracy along the X-axis and precision in the vertical plane's auditory localization. This latter result might be explained by the *perceptual deficit* hypothesis, according to which remaining sensory modalities manifest several deficits in processing spatial tasks (Pavani and Bottari, 2011), such as localization of sounds in the frontal plane (Lewald, 2002; Voss et al., 2015; Zwiers et al., 2001). In this sense, providing a multimodal stimulation to train auditory spatial abilities has overcome the impairment caused by the absence of visual cues (Bremner and Spence, 2008;

Lewkowicz, 2008; Shams and Seitz, 2008) and, consequently, of allocentric frames of reference to process auditory information when the sound source is moved in front of us.

Results showed a great improvement in accuracy after the audio-motor training in the correct match of the hand movement final position, but not in the correct body midline discrimination. According to previous literature, blind individuals show enhanced spatial abilities in immediate hand-pointing localization (Rossetti et al., 1996), probably related to the fact that visual experience during development seems to consolidate proprioceptive skills (Cappagli et al., 2015; Gori et al., 2010; Röder et al., 2004). Nevertheless, since spatial representation emerges thanks to the association between visual cues and motor skills (Bremner et al., 2008), visually impaired adults show delays in the acquisition of proprioceptive spatial abilities compared to sighted peers (Fraiberg, 1977; Landau et al., 1984; Warren, 1977). According to this latter statement, the multimodal training bridged the gap between residual proprioceptive abilities settled during the years of visual experience. It also seems to produce the difficulties in readapting the spatial coordinates system after visual loss, as shown in other works on auditory and proprioceptive improvement of visually impaired individuals after training audio-proprioceptive competencies (Cappagli et al., 2019, 2017; Finocchietti et al., 2017). Finally, the results on discrimination of body midline confirmed that, despite evident difficulties in referring to external landmarks, blind adults demonstrate superior abilities to solve spatial issues related to body-centered frames of reference (Kolarik et al., 2013; Vercillo et al., 2018). Indeed, LB participants performed the task correctly even before the training, suggesting a strong reliance on egocentric spatial cues (Cattaneo et al., 2008; Pasqualotto et al., 2013; Schmidt et al., 2013) that allows a veridical perception of their axis of body symmetry.

Overall, the present study emphasized that using a technology that provides auditory feedback associated to body movements can improve certain audio-proprioceptive spatial abilities in long-term late blind adults. Furthermore, our findings demonstrated that such training improved the accuracy and precision in the localization of sound sources in the frontal plane and the correct reproduction of a hand movement in the transverse plane. This results suggests that multimodal rehabilitation might help impaired individuals to overcome their spatial perceptual disabilities.

Chapter 4

General Discussion

The present doctoral thesis aimed at increasing current research knowledge related to the impact of visual deprivation on the developmental stages of spatial representation from childhood to adulthood (scientific objective), and validating the use of innovative technological systems for the assessment and rehabilitation of spatial competencies to enhance residual functions in the absence of visual input (technological objective). The first chapter of the thesis summarizes the main scientific findings related to the development and consolidation of spatial abilities in the visually impaired and the main technological systems developed to date to support visually impaired individuals in their daily activities. The second chapter presents a set of original studies where I assessed whether touch and hearing could favor the shift from a body-center (i.e., egocentric) towards an object-centered (i.e., allocentric) spatial perspective whenever a visual disability occurs. Finally, in the third chapter of the thesis, I presented the work done to develop and validate innovative technological devices that can evaluate spatial competencies in the presence of unisensory and multisensory stimulation and train visually impaired individuals through intact sensory modalities. In the present chapter, I will discuss the original studies' main outcomes presented in Chapter 3 and Chapter 4 with the final scope to reconcile them within the broader context or research literature investigating the impact of visual deprivation on spatial development.

4.1 Spatial representation with and without visual inputs

Several studies have demonstrated that vision plays a crucial role in the encoding of spatial information (Cappagli et al., 2015; Gori et al., 2012a; Thinus-Blanc and Gaunet, 1997; Vasilyeva and Lourenco, 2010; Vercillo et al., 2016) and is crucial for several cognitive spatial skills (Foulke, 1982; Thinus-Blanc and Gaunet, 1997). This is probably because the sense of sight prompts the development of an allocentric or object-centered frame of reference (e.g., referred to external landmarks (Foley et al., 2015; Klatzky, 1998)). It acts differently than other sensory modalities that mostly refer to egocentric or body-centered frames of reference (e.g., referred to the observer's body) as in case of touch. Consequently, the partial (i.e., low vision) or total (i.e., blindness) absence of visual experience can be detrimental for the consolidation of a spatial coordinates system based on egocentric and allocentric cues. Nonetheless, in Chapter 2 I presented a set of studies aiming at unraveling the impact of partial but permanent visual deprivation (Section 2.2) and total absence of visual experience (Section 2.3) on the development of switching perspective abilities, namely consisting in the ability to shift from an egocentric towards an allocentric spatial frame of reference. Results suggest that partial visual deprivation from birth prevents the development of allocentric spatial coding when comparing low vision and sighted children's performance in the visual domain (Section 2.2). Our findings are confirmed by previous studies on visually impaired adults, which showed their tendency to adopt reference frames mainly based on body landmarks due to a strong reliance on residual sensory modalities mainly, e.g. touch (Cattaneo et al., 2008; Pasqualotto et al., 2013). It has also been shown that visual loss prevents the use of external landmarks (Cattaneo et al., 2008; Iachini et al., 2014; Merabet and Pascual-Leone, 2010; Millar, 1994; Pasqualotto and Proulx, 2012; Schmidt et al., 2013; Thinus-Blanc and Gaunet, 1997) and affects switching-perspective abilities, namely the capacity to combine different reference frames in response to environmental changes (Cornoldi et al., 1991; Harris et al., 2012; Nadel and Hardt, 2004; Nardini et al., 2006; Vecchi et al., 2004). Other studies hypothesize that this might depend on the spatial task (Gaunet et al., 2007; Gaunet and Rossetti, 2006; Giudice et al., 2011; Rossetti et al., 1996). Our study presented in Section 2.2 highlights that visually impaired children perform egocentrically even when expected to solve a switching-perspective task. Indeed, they adopt allocentric frames of reference, contrarily to sighted peers who demonstrated a gradual improvement in the use of object-centered spatial references. During childhood, visual impairment delays the development of important spatial encoding abilities (Cappagli and Gori, 2016). Indeed, Ochaíta and Huertas (1993) found out that visually impaired children acquire a coherent sense of space at 17 years of age compared to sighted children's spatial maturation at 14 years of age. Such finding might be related to the lack of visuo-motor feedback that leads to locomotor delays during growth (Bremner et al., 2008; Fazzi et al., 2002; Fraiberg, 1977; Landau et al., 1984; Levtzion-Korach et al., 2000). Considering that egocentric and allocentric capabilities typically coexist until 6 years of age (Nardini et al., 2006; Newcombe and Huttenlocher, 2003) and are integrated after 8 years of age ((Bullens et al., 2010; Nardini et al., 2006); see also Nardini et al., 2008 (Nardini et al., 2008)), it seems that the process of spatial updating, included switching-perspective skills, is further delayed in blind individuals (Burgess, 2006; Cornoldi et al., 1991; Harris et al., 2012; Nadel and Hardt, 2004; Vecchi et al., 2004).

Recently, the hypothesis of a two-steps process in the development of spatial encoding has gained ground (Filimon, 2015). Specifically, in the first step spatial judgments are mainly based on an egocentric perspective, even when spatial locations are referred to external objects, while the second step implies a shift towards the use of objects-centered coordinates. According to such hypothesis, results reported in Section 2.2 would confirm that the presence of visual feedback facilitates the two-steps process, while an impoverished visual feedback prevents the emergence of the second step, anchoring individuals to an egocentric encoding without a mental spatial update. Further confirmation comes from neurophysiological studies on possible different processing of egocentric and allocentric spatial representation. For instance, Nadel and Hardt (2004) have shown that almost separate neural networks process allocentric and egocentric information, while Galati and colleagues (2010) demonstrated the activation of the posterior parietal/frontal network and of the posteromedial/medio-temporal cerebral substructures during egocentric and allocentric spatial coding, respectively.

Similarly to Section 2.2, our results in Section 2.3 show a significant difference in the spatial performance of sighted children who demonstrate the ability to switch from egocentric towards allocentric perspective in the visual condition of the task and blindfolded sighted peers who tend to maintain an egocentric perspective in the spatial representation of haptic stimuli. Further research supports our findings, reporting difficulties experienced by visually impaired children in performing a mental update of their position (Huttenlocher and Presson, 1973; Koustriava and Papadopoulos, 2012; Papadopoulos and Koustriava, 2011) or of objects' position (Huttenlocher and Presson, 1973; Papadopoulos and Koustriava, 2011; Penrod and Petrosko, 2003) in space. Our findings seem to be in line with the perceptual deficit hypothesis (see Chapter 1), which states that when visual feedback is missing, spatial performance in the tactile and auditory domains is compromised. Indeed, several studies demonstrate relevant difficulties in haptic orientation discrimination (Postma et al., 2008), updating of spatial information (Pasqualotto and Newell, 2007) and rotation of object arrays (Ungar et al., 1995), confirming the role of vision in refining residual sensory modalities spatial maps (King, 2009). Nonetheless, in Section 2.3 we also demonstrate that blind children perform better than blindfolded sighted children shifting from egocentric towards allocentric frames of reference in the haptic domain. This finding appears in conflict with previous literature on haptic mental rotation tasks, which indicates a predominant assumption of an egocentric perspective by blind individuals (Giudice, 2018; Millar, 1994; Schinazi et al., 2016; Ungar et al., 1995). Nevertheless, our result finds support in the study by Postma and colleagues (2007) that highlighted a better performance of blind compared to blindfolded sighted adults in the haptic processing of objects on a rotated platform when they based their judgments on objects and not on the platform itself as frames of reference. Consequently, they associated spatial encoding abilities of blind participants to the concept of “allocentric intrinsic spatial coding” (Brambring, 1982), different from the “allocentric extrinsic spatial coding” that assumes the surrounding environment as a reference. Concerning our results, a possible interpretation is that allocentric intrinsic haptic skills start to develop during childhood and consolidate in adulthood. Moreover, it might be supported by the *sensory compensation* theory (see Chapter 1), which show a great improvement in residual sensory modalities in the absence of visual inputs (Pavani and Bottari, 2011), as confirmed by several studies in the haptic domain (Benetti et al., 2017; Dehaene and Cohen, 2007; Hannagan et al., 2015; Kappers, 1999; Kappers and Koenderink, 1999; Klatzky, 1999; MacSweeney and Cardin, 2015). Another interesting finding of Sections 2.2 and 2.3 is the developmental delay showed by low vision and blind children in assuming a correct egocentric perspective when they need to perform a spatial task by crossing their body midline. In particular, they reproduce a spatial configuration of objects more mirror-like than egocentrically, while egocentric responses are given when the body midline is spatially aligned with the configuration. This result is supported by other works on the robust role of body midline as a reference point in case of alignment to coded objects (Millar, 1985, 1981) but not in body midline-crossing spatial tasks (Millar and Ittyerah, 1992). Furthermore, since egocentric spatial coding has also been considered centered on the eye (Rock, 1997), we might assume that visual loss centers the body-centered frame of reference on the body midline, regardless of objects' position.

In Chapter 2, I also presented one study investigating whether hearing can convey an object's spatial properties, which are typically conveyed by vision when sighted adults experience temporary visual deprivation (Section 2.4). Concerning the results reported in Section 2.4, our study indicates that audition promotes the discrimination of typical visual properties by conveying information about shapes' contours when vision is temporarily impaired. Although several studies have confirmed the importance of vision in the calibration process of the other non-visual modalities, i.e. hearing and touch, to represent environmental features (Eimer, 2004; Erdogan and Jacobs, 2017; Milner, 1974; Newell et al., 2005; Peelen et al., 2014; Pietrini et al., 2004). Other research works supported the theory that typically, visuo-spatial properties of objects, such as shape, can be conveyed by solely auditory cues (Bizley and Cohen, 2013; Carello et al., 1998). Further studies have demonstrated that audition can provide useful information about shape curvature (Boyer et al., 2015). The friction sounds produced by drawing an object let the listener recognize the drawn shape (Thoret et al., 2014). It has also been shown that audition can enhance sensorimotor contingencies by providing real-time feedback about objects' movements (Bevilacqua et al., 2016). Our results find support in the *sensory compensation* hypothesis, stating that residual sensory modalities – in this case, audition – compensate spatial deficits caused by visual impairment (Pavani and Bottari, 2011) by improving the performance in specific spatial tasks (Blauert, 2005; Bola et al., 2017; Lomber et al., 2010; Pascual-Leone and Hamilton, 2001; Salminen et al., 2012; Shiell et al., 2014) and recalibrating spatial abilities in both visually impaired children (Cappagli et al., 2019, 2017) and adults (Finocchietti et al., 2017). Such hypothesis is supported by studies demonstrating cross-modal plasticity mechanisms (Kolarik et al., 2014; Schenkman and Nilsson, 2010), that confirm the role of auditory information in the activation of cortical areas typically dedicated to visual stimuli processing (Collignon et al., 2006; Collignon and De Volder, 2009; Thaler et al., 2014). Such evidence indicates that audition might substitute vision to discriminate typically visual information about an object. For instance, Amedi and colleagues (2007) validated the use of a technology that converts visual images into soundscapes (i.e., a visual-to-auditory Sensory Substitution Device (SSD) (Bach-y-Rita and

Kercel, 2003; Gori et al., 2016; Meijer, 1992; Proulx and Harder, 2008), providing evidence that auditory cues can deliver spatial information about objects' shape and activate typically visual cortical areas, e.g. the lateral-occipital tactile–visual area (LOtv). Interestingly, Section 2.4 reports a better performance of blindfolded sighted adults in the discrimination of open- rather than closed-contour auditory shapes, showing an opposite pattern with respect to the visual domain. In support of our findings, Lewald and colleagues (2007) demonstrated that blind people are highly capable of processing shapes with open contours when conveyed as linear audio motion. Another possible interpretation might be related to the predominance of closed-contours shapes in the visual domain, since it has been demonstrated that two-dimensional visual closed-contour shapes are processed faster than open-contour shapes (Elder and Zucker, 1993). Further evidence has been provided by Gori and colleagues (2017), reporting a severe impairment of early-blind individuals in the correct perception and reproduction of sonorous geometrical shapes with closed contours. Consequently, audition seems to be less accurate and precise than vision to process certain spatial properties of an object, e.g. closeness of contours (Garrigan, 2012). Therefore, our result indicate that the ability to perceive auditory shapes with closed contours is altered by temporary visual deprivation.

To sum up, our findings provide evidence that permanent visual loss delays the integration of spatial reference systems across childhood, altering the developmental stages of spatial competencies, such as switching-perspective abilities. In particular, partial visual impairment leads to a stronger reliance on egocentric than allocentric frames of reference to solve a spatial issue by assuming a different perspective. Contrarily, the total absence of vision fosters haptic spatial skills during growth, allowing children to develop a coherent representation of complex spatial relations by relying on allocentric coordinates. Finally, we show that the temporary absence of visual input can enhance auditory spatial abilities in adults, providing effective means to process spatial features of an object that are typically identified by visual cues. These results suggest that vision typically conveys the most informative sensory input to comprehend spatial relations and properties of the environment (Thinus-Blanc and Gaunet, 1997). Other sensory modalities can also compensate for visual deprivation to develop and consolidate spatial coding skills. Moreover, our outcome highlights the importance of supporting the improvement of residual spatial competencies by developing innovative solutions for assessing and training spatial perceptual abilities in visually impaired individuals from childhood to adulthood.

4.2 Multisensory contingencies and technological development

Research has widely assessed the leading role of vision in processing multimodal spatial information with spatially and temporally coherent stimuli (Gori, 2015; Stein and Meredith, 1993). Therefore, we may suppose that visual impairment delays the multisensory integration of different sensory modalities and, consequently, the maturation of spatial representation abilities (Eimer, 2004; Van der Stoep et al., 2017). Novel technologies have been developed to substitute vision with residual senses, e.g. hearing and touch, and for assisted locomotion to support visual disability. Nonetheless, most of these systems have shown limitations towards both adults and, particularly, children (Cuturi et al., 2016; Gori et al., 2016).

In Chapter 3, I aimed at validating newly developed technologies to assess and enhance spatial skills to overcome the perceptual impairments observed in visually impaired population. Firstly, I presented innovative experimental tools (Sections 3.2.1., 3.2.2, and 3.2.3) to quantitatively evaluate unisensory and multisensory contingencies provided by visual, auditory and tactile stimuli with spatial and temporal congruency (Section 3.3.1), and to assess spatial interaction with moving unisensory targets (Section 3.3.2). Secondly, I validated the effects of training conducted using a recently developed device (Section 3.2.4) that provides multimodal contingencies in adults with temporary (Section 3.3.3) or permanent (Section 3.3.4) visual deprivation.

In Section 3.2, we presented a newly developed technological platform called *Interactive GYM* (*i-GYM*), intended as an interactive environment composed of independent multisensory devices to assess and train perceptual impairments from the first years of life. The first device is the *Technological ARM* (TechARM), designed as wireless, independent units providing spatially and temporally-coherent multisensory stimulation on the body with real-time feedback from the user of temporal reaction and spatial localization (Section 3.2.1). The second technology is the *Technological PAD* (TechPAD), consisting in multiple multisensory modules grouped in a cabled, unique and compact device with the main intent to investigate peripersonal spatial abilities in transverse and frontal planes (Section 3.2.2). Finally, the third prototype is the T*echnological MAT* (TechMAT), designed as a cabled system made of distinct but connectable modules that provide multimodal stimulation, with the main intent to realize a technological multisensory carpet through helping children in the exploration of extrapersonal space (Section 3.2.3).

The TechARM was the first developed and ready-to-test tool for the validation studies in Sections 3.2.1.3 and 3.2.1.4. The first validation study (Section 3.2.1.3) confirms the usability of the TechARM in conveying unisensory and multisensory spatial stimuli to investigate whether the size of the stimulated area has a detrimental or beneficial effect on sensory threshold, namely spatial summation effect. Spatial summation is a perceptual effect that has been studied with visual (Anderson and Burr, 1991, 1987; Burr et al., 1998), tactile (Gescheider et al., 2002; Verrillo et al., 1999; Verrillo and Gescheider, 1975) and pain (Marchand and Arsenault, 2002) stimulation, and at the cortical level, e.g. in the visual cortex areas (Shushruth et al., 2009). The second validation study (Section 3.2.1.4) confirms the efficacy of the TechARM to compare interception accuracy across different sensory modalities by varying the type and velocity of the stimulation.

Our results on spatial summation effects (Section 3.3.1) are in line with previous research on the crucial role of vision in driving multisensory interaction with the increasing of stimulated area, since it allows spatial encoding by referring to object-centered frames of reference (Monica Gori, 2015; Newell et al., 2005; Newport et al., 2002; B E Stein and Meredith, 1993), especially when stimuli are simultaneous (Foulke, 1982; Merabet and Pascual-Leone, 2010; Pasqualotto et al., 2013; Thinus-Blanc and Gaunet, 1997). Indeed, the influence of visual experience on spatial perception seems to foster the development of allocentric spatial skills (Nardini et al., 2009; Vasilyeva and Lourenco, 2012), improving spatial accuracy and precision of an event in case of multisensory interaction of stimuli congruent in space and in time [16]. For instance, bimodal visual-auditory (Miller, 1982) and visual-tactile (Diederich et al., 2003) stimulations provide reliable cues to discriminate spatial and temporal contingencies of a perceptual event (Miller, 1982; Todd, 1912). On the other hand, our findings point out that visual accuracy resulted in delayed responsiveness when a stimulated area's size increased, with a consequent worsening in terms of perceptual reaction, independently of unimodal or multimodal stimulation. A possible explanation of such results is that vision provides the highest reliability for a cognitive representation of peripersonal space, while audition and touch are based on less reliable frames of reference even if they provide a faster response to stimuli conveyed on the body. It might be that increasing the surface area on the body creates a conflicting event between sensory modalities based on different reference systems, so that vision might solve conflicting contingencies under a more cognitive point of view. Conversely, auditory and tactile stimuli foster perceptual abilities when a spatial summation of multiple stimuli takes place. Further motivations might be found in the coexistence of retinotopic and spatiotopic reference frames within the visual domain (Gardner et al., 2008; Golomb et al., 2008; Macaluso and Maravita, 2010; Wandell et al., 2007). Indeed, it has been demonstrated that the use of retinotopic coordinates can induce an error in processing the fovea's update towards a selected target, implying a more viewer-centered reference than spatiotopic coordinates (Noory et al., 2015). According to this view, retinotopic and spatiotopic frames of reference might get into a perceptual conflict when visual stimuli are conveyed within peripersonal space that leads to a significant delayed responsiveness.

Interestingly, our study points out a possible leading role of touch toward audition with increasing audio-tactile bodily area, considering that the combination of auditory and tactile stimuli results in a better performance than unimodal stimulation when the size of stimulation increases. A possible explanation might be that when external (auditory) and body-centered (tactile) references are combined in the absence of visual inputs, major stability in terms of spatial performance takes place together a consequent smaller unisensory uncertainty bigger area of stimulation. In support of this idea, previous works showed a convergence between auditory and tactile stimuli in the case of spatiotemporal coherence (Foxe, 2009), further supported by evidence on the early convergence and integration of auditory and tactile inputs at sensory cortices level (Brandwein et al., 2011; Finocchietti et al., 2015b; Foxe et al., 2002, 2000; Keniston et al., 2010; Meredith et al., 2009; Schroeder et al., 2001). Other works support the theory of dominance of touch over audition when conveyed with spatial and temporal coherency within peripersonal borders (Hötting and Röder, 2004; Sherrick, 1976; Soto-Faraco et al., 2004), even though body posture changes may alter this interaction (Sanabria et al., 2005; Soto-Faraco et al., 2004).

Concerning the ability to intercept moving stimuli on the body (Section 3.3.2), our findings demonstrate that auditory and tactile information is as useful as visual cues to build a bodily map for the localization (in case of static target) and interception (in case of moving target) on the arm. When static stimuli are conveyed, vision prevails over audition and touch for velocity and precision of responses. We might argue that the spatial and temporal resolution of the visual system plays a crucial role in improving spatial localization skills, depending on the high resolution of the fovea (Danilova and Bondarko, 2007), while the resolution of skin receptors on the arm (Cholewiak et al., 2004) might be different with respect to the spatial resolution of tactile stimuli conveyed by the TechARM, thus producing more uncertainty.

Interestingly, opposite velocities of dynamic targets result in different perceptual processing of auditory and tactile stimuli, since slow targets induce a similar response for vision and touch but worsen for audition, while fast targets see a similar performance for vision and audition but worsen for touch. The first outcome can be confirmed by previous literature on tactile and visual interception tasks, showing a similar result with low velocities (Nelson et al., 2019), while other literature finds a similar result on high interceptive performance with fast auditory stimuli (Komeilipoor et al., 2015). Furthermore, hearing has been considered the most accurate sense to develop orientation and mobility skills by relying on distal environmental cues (Gori, 2015) and to substitute vision in conveying spatial properties of an object (Amedi et al., 2007; Bizley and Cohen, 2013; Boyer et al., 2015; Carello et al., 1998). Several studies on auditory motion detection have also shown that head motion might affect the localization of auditory moving targets in blind (Vercillo et al., 2017) but not in sighted (Finocchietti et al., 2015b; Lewald, 2013; Zwiers et al., 2001) individuals, probably due to a stronger reliance on body-centered frames of reference when vision is absent. Overall, our findings suggest that the TechARM system is suitable for investigating unisensory and multisensory spatial perception and provide evidence that the use of such technology for specific training and rehabilitation protocols based on multisensory stimulation might enhance residual perceptual skills in case of visual disability (i.e., low vision and blindness) across development.

Starting from the need to provide multisensory contingencies to train residual spatial abilities when vision is absent, Chapter 3 introduces (Section 3.2.4) and demonstrates the efficacy of a wearable device called ABBI (Finocchietti et al., 2015c; Porquis et al., 2017), included in the assessment and rehabilitation system called ABBI-K system (Martolini et al., 2018). ABBI provides auditory feedback of body movements to train auditory spatial skills in blindfolded adults (Section 3.3.3) and enhances audio-proprioceptive spatial skills in long-term late blind adults (Section 3.3.4). The choice to adopt a multisensory approach to visually impaired individuals' spatial skills has gradually increased in importance (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008). Indeed, multisensory redundancy of coherent cross-modal stimuli seems to be helpful for the detection of the amodal properties of events (Bahrick et al., 2004). For instance, the multisensory association of audition and motion enhances sensorimotor learning and motor control and fosters rehabilitation and sport training (Schaffert et al., 2019; Scholz et al., 2014). Recently, the efficacy of ABBI for multimodal training has been assessed for the improvement of spatial representation skills in blind children (Cappagli et al., 2019, 2017) and adults (Finocchietti et al., 2017). Indeed, multimodal stimulation seems more effective than unimodal stimulation in providing spatial information of the environment (Bahrick et al., 2004; Shams and Seitz, 2008).

Our results indicate that blindfolded sighted adults improve the recognition of open-contour auditory shapes thanks to during a short training with ABBI, based on the coupling of auditory and motor feedback of their own body movements (Section 3.3.3). A similar outcome was confirmed by Aggius-Vella and colleagues (2017), demonstrating an enhancement of spatial coding skills after audio-motor training in sighted adults, as well as previously shown in blindfolded sighted adults (Boyer et al., 2013) and visually impaired individuals (Bolognini et al., 2005; Cappagli et al., 2019, 2017; Finocchietti et al., 2017; Frassinetti et al., 2005; Grasso et al., 2016; Passamonti et al., 2009). A possible explanation of such result might be related to creating a ‘bridge’ between body representation and external representation that can be exploited to shift from an egocentric towards an allocentric spatial representation. In the absence of visual inputs, hearing can mediate recalibration of the extra-personal space in allocentric coordinates from body-centered coordinates. According to this view, audition has acquired importance in conveying spatial information thanks to the development of Sensory Substitution Devices (SSDs), intended as technological solutions converting visual properties of a stimulus into auditory or tactile information (Amedi et al., 2007; Auvray and Myin, 2009; Bach-y-Rita and Kercel, 2003; Cuturi et al., 2016; Gori et al., 2016; Meijer, 1992; Proulx and Harder, 2008; Velázquez, 2010). However, SSDs typically substitute but do not rehabilitate impaired spatial abilities, they do not provide any multimodal contingencies (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008), and they expect a high cognitive load that is detrimental, especially for children (Cuturi et al., 2016; Gori et al., 2016).

Interestingly, our results further show a beneficial effect of the audio-motor training only to recognize auditory open-contour shapes. We might speculate on the possibility that the proposed audio–motor training might led to generalization to, at least, novel untrained auditory open-contour shapes, while closed-contour shapes need a different training methodology.

Alternatively, we might suppose that a training based on audition fosters a recalibration of open-contour shapes, which are less frequent in everyday life, while closed-contour shapes are considered typically visual spatial properties to discriminate objects in the environment. Indeed, it is even possible that closure is less predominant in audition than vision.

Focusing on spatial performance of blind adults (Section 3.3.4), our results assess that the use of ABBI in a one-month rehabilitation program based on the coupling of auditory and motor feedback improves certain audio-proprioceptive spatial abilities in long-term (i.e., more than 20 years) late blind (LB) adults. In sound source localization on the horizontal plane, participants maintain the same accuracy and precision before and after the training, while the training fostered a better performance in the localization of static sounds in the frontal plane. Our results are in line with previous literature on blind adults, that shows superior auditory abilities in the transverse plane (Doucet et al., 2005; Gougoux et al., 2004; King and Parsons, 1999; Lessard et al., 1998; Lewald, 2007; Roder et al., 1999) compared to blindfolded sighted peers (Abel et al., 2002; Tabry et al., 2013), further confirmed by the recruitment of the visual cortex to process auditory spatial cues (Gougoux et al., 2005; Poirier et al., 2005; Renier and De Volder, 2005; Striem-Amit and Amedi, 2014; Weeks et al., 2000). Conversely, according to the *perceptual deficit* hypothesis (see Chapter 1), residual senses are impaired in solving specific auditory spatial tasks (Pavani and Bottari, 2011) in the frontal plane (Lewald, 2002; Voss et al., 2015; Zwiers et al., 2001). In this sense, providing a multimodal stimulation to train auditory spatial abilities has overcome the impairment caused by the absence of visual cues (Bremner and Spence, 2008; Lewkowicz, 2008; Shams and Seitz, 2008) and, consequently, allocentric frames of reference to process auditory information when the sound source is moved in front of us.

Concerning proprioceptive tasks, our findings confirm the efficacy of the multisensory training to match the final position of the hand movement correctly, but do not show any difference in the definition of the body midline. Despite it has been shown that blindness is not detrimental for the development of proprioceptive skills (Cappagli et al., 2015; Gori et al., 2010; Röder et al., 2004), such in case of immediate hand-pointing localization tasks (Rossetti et al., 1996), visually impaired adults manifest less accurate proprioceptive spatial abilities than sighted peers (Fraiberg, 1977; Landau et al., 1984; Warren, 1977). To overcome such impairments, the multimodal training might act as a “bridge” to fill the gap between residual proprioceptive abilities settled during the years of visual experience and the spatial difficulties encountered after visual loss (Cappagli et al., 2019, 2017; Finocchietti et al., 2017). On the other hand, the correct discrimination of the body midline can be reduced to the superior spatial abilities related to body-centered frames of reference (Kolarik et al., 2013; Vercillo et al., 2016), since blind individuals demonstrate a strong reliance on egocentric spatial cues (Cattaneo et al., 2008; Pasqualotto et al., 2013; Schmidt et al., 2013).

To conclude, our findings highlight the relevance of multisensory information to define spatial properties and the importance of training spatial competencies by providing multimodal contingencies, with particular attention to partial and total permanent visual loss that alters the development and consolidation of spatial coding abilities. Due to the lack of assessment and rehabilitation tools to convey multisensory stimulations, we proposed and validated new technological systems to overcome the perceptual impairments observed in the visually impaired population. In particular, when multisensory integration is driven by vision, it improves response accuracy when the stimulated area increases, since it provide a more reliable reference system to encode peripersonal space (e.g., allocentric), but delays responsiveness to stimulation, contrarily to bimodal audio-tactile stimulation. Moreover, auditory and tactile information can help intercept a target on the arm, depending even on the velocity of dynamic stimuli. Furthermore, temporary visual deprivation benefits from the coupling of auditory feedback and body movements to foster the recognition of auditory shapes outside the body. Adults experiencing long-term late blindness take advantage of audio-motor training based on bodily cues to improve auditory and proprioceptive spatial competencies. These results suggest that a multisensory approach is more suitable than unisensory information (Bahrick et al., 2004; Shams and Seitz, 2008) to train and eventually rehabilitate spatial competencies when vision is temporary or permanently impaired. Consequently, the need to design and validate technological devices to assess and support multisensory skills in visually impaired people can guarantee an improvement in autonomy and an increment of exploratory opportunities thanks to rehabilitation programs instead of substituting intents.

4.3 Further works

The present thesis intends to increase knowledge about visual impairment on the developmental and consolidation of spatial coding skills in children and adults, respectively (see Chapter 2), and to propose original experimental protocols with the inclusion of newly developed technological systems to provide assessment methods and training tools for the promotion of spatial competencies rehabilitation for visually impaired individuals (see Chapter 3).

In addition to the findings presented in Chapters 2 and 3, I introduce two preliminary works that aim to deepen auditory spatial competencies without any visual clues in case of moving targets (Section 4.3.1) and to assess whether a training based on the coupling of audio-visual and motor feedback of body movements provided by the device ABBI would boost the spontaneous recovery in cataract-treated children (Section 4.3.2).

4.3.1 Movement-induced bias in auditory spatial perception

Research on localizing a moving stimulus has increasingly acquired relevance, since humans continuously keep tracking of changes in the spatial position of visual and auditory objects in real environments. In the visual domain, spatial biases are known to affect the perceived onset of motion, i.e. the *Fröhlich Effect* (Fröhlich, 1923) and the final position of motion, i.e. the *Representational Momentum Effect* (Freyd and Finke, 1984). The Fröhlich Effect describes a phenomenon where the initial position of a moving stimulus is perceived as shifted in the direction of motion (Fröhlich, 1923; Kerzel and Gegenfurtner, 2004; Kirschfeld and Kammer, 1999; Müsseler and Aschersleben, 1998), while the Representational Momentum Effect is a bias of the final position in the direction of motion (Freyd and Finke, 1984; Hayes and Freyd, 2002; Hubbard, 2005). It has been hypothesized that such visual effects might depend on target velocity, attention, target position, and response measure (Hubbard, 2005; Kerzel, 2003). Since both effects describe a spatial displacement in the movement direction, it has been proposed a common underlying mechanism for determining the onset and offset position of a moving visual stimulus (Müsseler et al., 2002; Whitney and Cavanagh, 2000). In audition, fewer studies have investigated what happens in the localization of the onset (Getzmann, 2005a; Perrott and Musicant, 1977) or offset (Feinkohl et al., 2014; Getzmann, 2005b; Getzmann et al., 2004; Perrott and Musicant, 1977) of moving sounds. A comparison of the Representational Momentum Effect in the visual and auditory domains (Schmiedchen et al., 2013) found similar dependence on the target's spatial location, stimulus velocity, and direction, but significant differences in the magnitudes of displacement for each modality.

Moreover, conflicting results have been shown on the effect of velocity in the end-point localization for stimuli moving towards the setup periphery (Feinkohl et al., 2014; Schmiedchen et al., 2013). It remains unclear whether spatial information might affect the perception of a moving stimulus in the auditory domain.

This study aims to shed light on how velocity influences the localization of onset (*Fröhlich* effect) and offset (*Representational Momentum* effect) of an auditory moving target on typical sighted adults, evaluating whether the result is comparable to research findings on visual movement-induced biases in the direction of motion.

Sample and Task procedure

Eight adults with normal visual and auditory acuity were recruited for the experiment, performed in a dark room, after signing the informative consent according to the Declaration of Helsinki. Auditory stimuli are provided through a set of 18 loudspeakers covered with 4X4 arrays of tactile sensors (Vercillo et al., 2017), placed inside a fixed 120° arc mechanical support with a distance of 6.67° between two consecutive speaker centers (Figure 4.1a). Participants sit at a distance of 50 cm from the loudspeakers, facing the central speakers 9 and 10. They are asked to look at a physical fixation marker (a cross) between the central loudspeakers to prevent ocular movements. The moving sound produced is a white noise burst with 300 Hz center frequency, and the stimuli move randomly from the left to the right side of the setup, or vice-versa. The movement's velocity is pre-determined and maintained constant

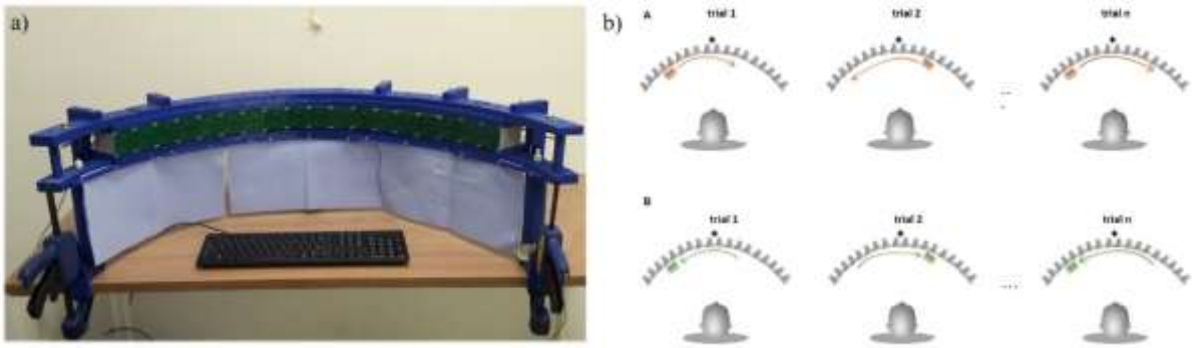

Figure 4.1 Setup and example of the moving stimuli in the auditory Fröhlich and Representational Momentum effects.
(a) The setup consists in a set of 18 loudspeakers covered with 4X4 arrays of tactile sensors, fixed in 120° arc mechanical support. (**b)** The moving stimuli during the experimental trials. **A)** The participant listens to a moving stimulus, with variable starting and ending positions, then he/she is required to touch the surface of the perceived starting loudspeaker (evaluation of the Fröhlich effect). The velocity of the moving sound is pre-determined, and the direction is randomized. **B)** The participant is required to locate the offset of the moving stimulus by touching the surface of the perceived ending loudspeaker (evaluation of the Representational Momentum effect). The velocity of the moving sound is pre-determined, and the direction is randomized.

(three targeted velocities: 20°/s, 30°/s, 40°/s), while different spatial displacements between the onset and offset of the sound are pre-determined and randomized. The target (onset for Fröhlich effect, see Figure 4.1bA; offset for Representational Momentum effect, see Figure 4.1bB) is pre-determined and randomized among all the trials. The experiment is performed in two separate sessions, in which they are asked to touch the perceived onset or offset position after the moving sound stopped.

Preliminary results

Preliminary findings show a strong Fröhlich effect (mean bias: 7.66° ± 0.10) but a weaker Representational Momentum effect (mean bias: 1.05° ± 0.11) in the auditory modality. The analysis of onset (Figure 4.2A) and offset (Fig. 4.2B) motions indicated that fast stimuli (40°/s) induced a larger spatial bias than medium (Fröhlich: $p < 0.05$; Representational Momentum: $p < 0.05$) and lower (Fröhlich: $p < 0.001$; Representational Momentum: $p < 0.001$) velocities in the direction of motion. This work suggests that increasing the velocity of an auditory moving

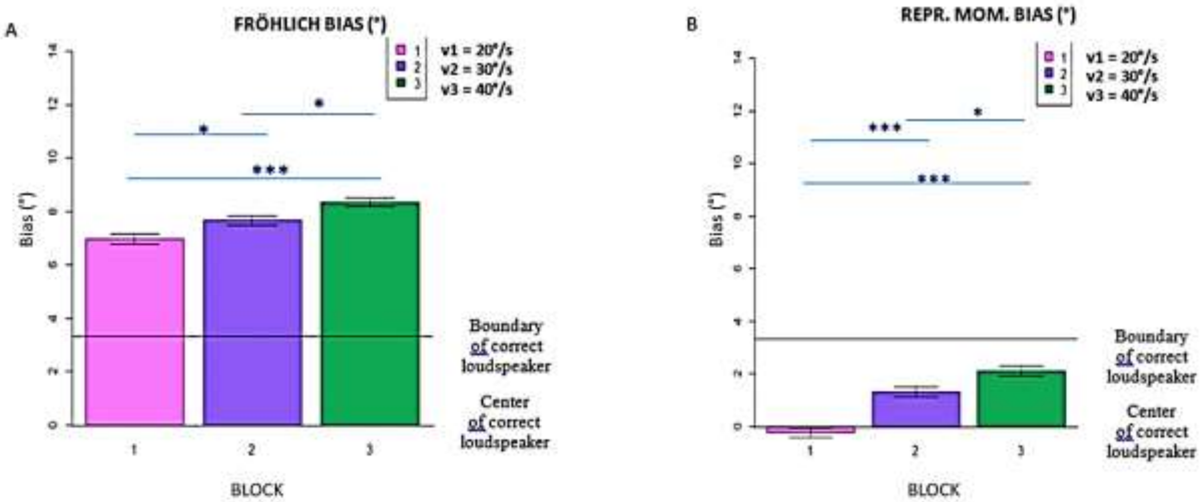

Figure 4.2 Preliminary findings of movement-induced bias in spatial perception of a moving sound. **A)** The analysis of onset indicated that fast stimuli (40°/s) induced a larger spatial bias than medium ($p < 0.05$) and lower ($p < 0.001$) velocities in the direction of motion. **B)** The analysis of offset indicated that fast stimuli (40°/s) induced a larger spatial bias than medium ($p < 0.05$) and lower ($p < 0.001$) velocities in the direction of motion.

sound might increase the shifts in the spatial perception of the starting and ending position in the direction of motion.

4.3.2 Effects of audiovisuo-motor training on spatial recalibration in cataract-treated children

Research on dense congenital and infantile cataracts has shown that it should be treated as soon as it arises. Otherwise, it may lead to a progressive and sometimes irreversible complete visual loss (Birch et al., 2009). Despite several studies on visual functions after sight restoration have shown a normal development of spatial properties of the environment, such as color perception (Brenner et al., 1990; McKyton et al., 2015; Pitchaimuthu et al., 2019) or biological motion detection (Bottari et al., 2015; Hadad et al., 2012), other works pointed out the existence of permantent visual impairments, such as reduced visual acuity (Ellemberg et al., 1999; Kalia et al., 2014), difficulty in face processing (Le Grand et al., 2001; Putzar et al., 2010), and reduced global motion perception (Bottari et al., 2018; Hadad et al., 2012). Concerning children, it has been demonstrated that the visual impairment is experienced more in the case of monocular than binocular cataract and depends on the cataract onset (Lewis and Maurer, 2005). In particular, children treated for congenital cataracts later in life show relevant delays in the development of visuo-spatial skills, such as reduced ability to integrate body-centered and object-centered frames of reference into a unique spatial coding system (Geldart et al., 2002; Lewis et al., 2002).

The main aim of this study is to investigate whether the use of the device ABBI (Finocchietti et al., 2015c; Porquis et al., 2017) for specific training based on auditory, visual and motor feedback of body movements would rapidly improve the recovery of normal visual functionalities in cataract-treated children (Senna et al., 2020).

Sample and Task procedure

Eighteen post-treatment Ethiopian children (congenital dense bilateral cataract, surgically treated years after birth), and nine blind or low vision controls (5 Ethiopian, 4 Italian children) participate in the experimental protocol, after their parents or legal guardians have sighed informed consent. The battery of evaluative tests proposed to the experimental groups before and after the training (only cataract-treated participants) includes: i) auditory bisection task, consisting in listening to three consecutive auditory stimuli played at three different spatial positions, and evaluating the spatial distances between the three sounds; ii) audio-visual localization task, consisting in the localization of single sounds or single visual stimuli in a large 2d space (thus, in both the vertical and horizontal planes (Finocchietti et al., 2015b)); iii) reaching for static sound task, consisting in listening to a static sound for 5 seconds, and then reaching the position of the sound by walking towards it (3 random positions x 3 times)

(Finocchietti et al., 2015c); iv) mobility task, consisting in walking from a starting position until the experimenter touches the participant's shoulder, and walking back to the origin position as fast as possible (3 times) (Cappagli et al., 2019; Finocchietti et al., 2015c); v) pointing straight ahead (body midline) task, consisting in pointing straight forward, at the height of the shoulder, touching a dedicated setup (Finocchietti et al., 2015b).

The training with ABBI lasted one week (evaluation included) for a group of children and only post-treatment children participate in the training sessions. The control group is tested twice after 5/6 days from the first evaluation to make sure that possible improvements observed in the training group are not merely due to familiarity with the tasks. Each day the first training session lasts 45 min, while the second session lasts about 30 min. During the training, ABBI provides both auditory and visual stimuli (activation of the LED) and it is associated to body movements in tasks involving audio-motor and audio-visuo-motor associations, previously proposed by Cappagli and colleagues (2019).

Preliminary results

Auditory bisection task. Results show that cataract-treated children improved in the task (Figure 4.3A), with a smaller threshold after the training than the performance before the training. Instead, blind control participants show comparable performance in the first and second evaluation tests, ruling out the possibility that an eventual improvement could be merely related to familiarity with the task.

Audio-visual localization task. The overall accuracy, measured as the mean linear error between each target and pointing, and precision, measured as the variance of all errors, are calculated for each participant. Figure 4.3B shows the mean pointing error and the mean variance across participants in the visual and auditory conditions. Post-treatment participants significantly improve their accuracy after the training, and they tend to improve in their precision. Blind and low vision controls show similar behavior in the two tests.

Reaching for static sound task. The accuracy is calculated in each participant as the median linear error between the target and the position reached by the participant. The precision is measured as the variance of the residuals (i.e., calculating the median localization error and subtracting it from individual trials, then taking the variance of such differences as a measure of precision). Figure 4.3C shows that children taking part in the training significantly reduce the linear error (i.e., higher accuracy) and improve their precision, while blind children did not

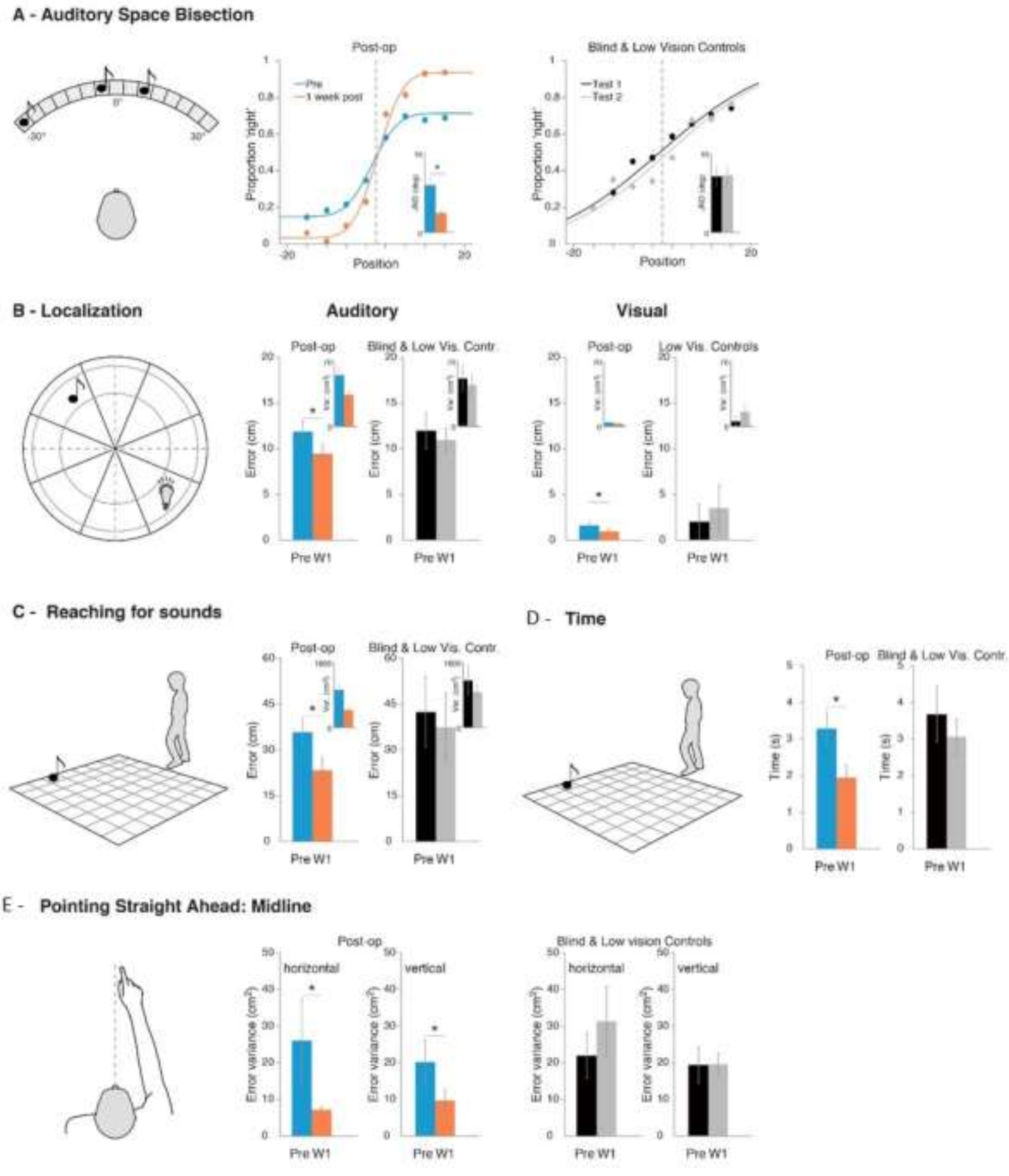

Figure 4.3 Results after one week of training with ABBI in cataract-treated children.
A) Results in auditory bisection task show that cataract-treated children improved in the task, with a smaller thresholds after the training, as compared to the performance before the training. Blind control participants do not improve in the second evaluation tests. **B)** Results in the auditory-localization task show that post-treatment participants tend to improve after the training, while blind and low vision controls show a similar behavior in the two tests. **C)** In the reaching for single sound task, children taking part in the training significantly reduce the linear error (i.e., higher accuracy) and improve their precision, while blind children did not reduce their variance. The control group do not show any improvement between the first and the second test. **D)** Results in the mobility task show that post-treatment children reduce the time to go back to the starting position already after one week of training, while blind and low vision controls do not change their performance between the two tests. **E)** In the pointing straight ahead task, post-treatment children become significantly more precise along the vertical axis after one week of training, showing a similar trend for the horizontal axis. On the contrary, blind and low vision controls do not differ between the first and second test.

reduce their variance. The control group does not show any improvement between the first and the second test.

Mobility task. The time from the touch of the participant's shoulder to when the child was back to the origin position is recorded with a stopwatch. In Figure 4.3D, post-treatment children reduce the time to go back to the starting position already after one week of training, while blind and low vision controls do not change their performance between the two tests.

Pointing straight ahead task. Figure 4.3E shows the median variance of the pointing errors across participants. In each trial, the pointing error is measured as the distance between the target (i.e., the center of the circle, aligned with the mid-sagittal plane and at the height of the shoulder) and the endpoint of the participant's pointing along the horizontal axis, where negative values indicate errors on the left of the target, and the vertical axis, where negative values indicate error below the target. The variance in the pointing trials along the horizontal and vertical axes is taken as a measure of precision. Post-treatment children become significantly more precise along both the vertical and horizontal axes after one week of training. On the contrary, blind and low vision controls do not differ between the first and second tests.

Overall, these findings suggest that cataract-treated children benefit from a short training with ABBI, sometimes even getting to values within normal range (bisection task), only after one week of training.

4.4 Concluding remarks

The present thesis had the main aim to: increase knowledge related to spatial development following partial or total lack of visual experience; present new methodologies based on innovative experimental paradigms and technological systems to assess spatial coding skills in response to unisensory and multisensory contingencies; to promote multimodal rehabilitation training to foster residual sensory modalities in building a clear and stable spatial map of the environment. Our results point out that visual deprivation impairs the development of integrated spatial reference systems, maintaining a tendency to encode space by referring almost to an egocentric perspective, even though the reliance on haptic skills partially overcomes the difficulty of assuming a more allocentric point of view. Moreover, further enhancements are shown in the auditory domain when vision is temporarily impaired, providing unusual processing methods to encode spatial features of the environment, supporting the idea that the absence of visual inputs can be compensated by other sensory modalities (Pavani and Bottari, 2011). Despite the necessity to further investigate the grade of spatial confidence provided by touch in individuals with visual impairment, our outcome supports the importance of relying on residual spatial competencies by developing innovative solutions that can be affordable for both children and adults. Several studies have shown that multisensory integration can convey a more accurate and precise representation of the environment and foster solid relations between the body and objects in space (Deneve and Pouget, 2004; Barry E. Stein and Meredith, 1993) in a statistically optimal manner (Alais and Burr, 2004; Ernst and Banks, 2002; Gori et al., 2013, 2012b, 2011; Squeri et al., 2012; Stein, 2012; Barry E. Stein and Meredith, 1993; Tomassini et al., 2011; Trommershauser et al., 2011). Our findings confirm the importance of providing multimodal contingencies to improve spatial competencies to compensate and rehabilitate developmental delays due to partial and total permanent visual loss. The actual lack of assessment and rehabilitation tools that can provide multisensory contingencies within peripersonal space prompts us to propose and validate new technologies to train residual perceptual abilities to improve visually impaired individuals' spatial coding skills. In the current thesis, we used an innovative device to investigate the impact of multisensory interaction on spatial discrimination with increasing dimensions of the stimulated bodily area, highlighting that bimodal audio-tactile stimulation can potentially convey spatial information in the absence of visual inputs. Unisensory auditory and tactile information helps intercept moving stimuli on the body, providing further evidence of the importance of enhancing spatial information of other senses than vision. Multimodal contingencies provided during rehabilitation training demonstrate to be crucial to foster the discrimination of auditory spatial properties of the environment, such as objects' shape, in temporary visual deprived individuals, and to improve auditory and proprioceptive spatial competencies in blind adults taking advantage of the association between sounds and body movements. Our outcomes might have important implications for the definition of novel rehabilitation and training protocols, shedding light on the role played by residual sensory modalities with atypical development of visual experience.

Therefore, future works will encourage further investigation in multisensory contingencies with and without visual inputs, with potential implications for developing appropriate rehabilitation training suitable for both children and adults with visual impairment.

List of publications

Martolini, C., Cuppone, A. V, Cappagli, G., Finocchietti, S., Maviglia, A., Gori, M., 2018. ABBI-K: a novel tool for evaluating spatial and motor abilities in visually impaired children, in: *2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA). IEEE*, pp. 1–6

Martolini, C., Cappagli, G., Campus, C., Gori, M., 2020. Shape recognition with sounds: improvement in sighted individuals after audio–motor training. *Multisens. Res. 33*, 417–431.

Martolini, C., Cappagli, G., Luparia, A., Signorini, S., Gori, M., 2020. The impact of vision loss on allocentric spatial coding. *Front. Neurosci.* 14, 565.

Martolini, C., Cappagli, G., Signorini, S., Gori, M., 2021. Effects of Increasing Stimulated Area in Spatiotemporally Congruent Unisensory and Multisensory Conditions. *Brian Sciences* 11(3), 343.

Martolini, C., Cappagli, G., Saligari, E., Gori, M., Signorini, S., 2021. Allocentric spatial perception through vision and touch in sighted and blind children. *Journal of experimental child psychology* 210, 105195.

Schiatti, L., Cappagli, G., **Martolini**, C., Maviglia, A., Signorini, S., Gori, M., Crepaldi, M., 2020. A Novel Wearable and Wireless Device to Investigate Perception in Interactive Scenarios, in: *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE*, pp. 3252–3255.

Ahmad, H., Tonelli, A., Crepaldi, M., **Martolini**, C., Capris, E. and Gori, M., 2020, July. Audio-Visual Thumble (AVT): A low-vision rehabilitation device using multisensory feedbacks. In *2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)* (pp. 3913-3916). *IEEE*.

Senna, I., Pfister, S., **Martolini**, C., Gori, M., Cocchi, E., Ernst, M.O., 2020. Spatial recalibration in cataract-treated individuals. *J. Vis. 20*, 1011

References

Abel, S.M., Figueiredo, J.C., Consoli, A., Birt, C.M., Papsin, B.C., 2002. The effect of blindness on horizontal plane sound source identification: El efecto de la ceguera en la identificatión de la fuente sonora en el piano horizontal. Int. J. Audiol. 41, 285–292.

Acredolo, L.P., 1981. Small-and large-scale spatial concepts in infancy and childhood. Spat. Represent. Behav. across life span theory Appl. by LS Liben, AH Patterson, N. Newcom.

Adelson, E., Fraiberg, S., 1974. Gross motor development in infants blind from birth. Child Dev. 114–126.

Aggius-Vella, E., Campus, C., Finocchietti, S., Gori, M., 2017. Audio motor training at the foot level improves space representation. Front. Integr. Neurosci. 11, 36.

Aggius-Vella, E., Gori, M., Animali, S., Campus, C., Binda, P., 2020. Non-spatial skills differ in the front and rear peri-personal space. Neuropsychologia 147. https://doi.org/10.1016/j.neuropsychologia.2020.107619

Alais, D., Burr, D., 2004. The ventriloquist effect results from near-optimal bimodal integration. Curr. Biol. 14, 257–262.

Amadeo, M.B., Campus, C., Gori, M., 2020. Years of Blindness Lead to "Visualize" Space Through Time. Front. Neurosci. 14, 812.

Amadeo, M.B., Campus, C., Gori, M., 2019. Time attracts auditory space representation during development. Behav. Brain Res. 376. https://doi.org/10.1016/j.bbr.2019.112185

Amedi, A., Stern, W.M., Camprodon, J.A., Bermpohl, F., Merabet, L., Rotman, S., Hemond, C., Meijer, P., Pascual-Leone, A., 2007. Shape conveyed by visual-to-auditory sensory substitution activates the lateral occipital complex. Nat. Neurosci. 10, 687–689.

Anderson, P.W., Zahorik, P., 2011. Auditory and visual distance estimation, in: Proceedings of Meetings on Acoustics 161ASA. Acoustical Society of America, p. 50004.

Anderson, S.J., Burr, D.C., 1991. Spatial summation properties of directionally selective mechanisms in human vision. JOSA A 8, 1330–1339.

Anderson, S.J., Burr, D.C., 1987. Receptive field size of human motion detection units. Vision Res. 27, 621–635.

Ashmead, D.H., Hill, E.W., Talor, C.R., 1989. Obstacle perception by congenitally blind children. Percept. Psychophys. 46, 425–433.

Ashmead, D.H., Wall, R.S., Ebinger, K.A., Eaton, S.B., Snook-Hill, M.-M., Yang, X., 1998. Spatial hearing in children with visual disabilities. Perception 27, 105–122.

Auvray, M., Myin, E., 2009. Perception with compensatory devices: From sensory substitution to sensorimotor extension. Cogn. Sci. 33, 1036–1058.

Aytekin, M., Moss, C.F., Simon, J.Z., 2008. A sensorimotor approach to sound localization. Neural Comput. 20, 603–635.

Bach-Y-Rita, P., Collins, C.C., Saunders, F.A., White, B., Scadden, L., 1969. Vision substitution by tactile image projection. Nature 221, 963–964. https://doi.org/10.1038/221963a0

Bach-y-Rita, P., Kercel, S.W., 2003. Sensory substitution and the human-machine interface. Trends Cogn. Sci. https://doi.org/10.1016/j.tics.2003.10.013

Bahrick, L.E., Lickliter, R., Flom, R., 2004. Intersensory redundancy guides the development of selective attention, perception, and cognition in infancy. Curr. Dir. Psychol. Sci. 13, 99–102.

Bai, S., Wang, X., Bai, X., 2014. Aggregating contour fragments for shape classification, in: 2014 IEEE International Conference on Image Processing (ICIP). IEEE, pp. 5252–5256.

Baillargeon, R., 1987. Object permanence in 3½-and 4½-month-old infants. Dev. Psychol. 23, 655.

Baillargeon, R., DeVos, J., 1991. Object permanence in young infants: Further evidence. Child Dev. 62, 1227–1246.

Baillargeon, R., Spelke, E.S., Wasserman, S., 1985. Object permanence in five-month-old infants. Cognition 20, 191–208.

Bayley, N., 1993. Bayley scales of infant development: Manual. Psychological Corporation.

Benetti, S., van Ackeren, M.J., Rabini, G., Zonca, J., Foa, V., Baruffaldi, F., Rezk, M., Pavani, F., Rossion, B., Collignon, O., 2017. Functional selectivity for face processing in the temporal voice area of early deaf individuals. Proc. Natl. Acad. Sci. 114, E6437–E6446.

Bertelson, P., Aschersleben, G., 2003. Temporal ventriloquism: crossmodal interaction on the time dimension: 1. evidence from auditory–visual temporal order judgment. Int. J. Psychophysiol. 50, 147–155.

Bevilacqua, F., Boyer, E.O., Françoise, J., Houix, O., Susini, P., Roby-Brami, A., Hanneton, S., 2016. Sensori-motor learning with movement sonification: perspectives from recent interdisciplinary studies. Front. Neurosci. 10, 385.

Bigelow, A.E., 1996. Blind and sighted children’s spatial knowledge of their home environments. Int. J. Behav. Dev. 19 (4), 797–816.

Birch, E.E., Cheng, C., Stager Jr, D.R., Weakley Jr, D.R., Stager Sr, D.R., 2009. The critical period for surgical treatment of dense congenital bilateral cataracts. J. Am. Assoc. Pediatr. Ophthalmol. Strabismus 13, 67–71.

Bizley, J.K., Cohen, Y.E., 2013. The what, where and how of auditory-object perception. Nat. Rev. Neurosci. 14, 693–707.

Blasch, B.B., Welsh, R.L., 1980. Training for persons with functional mobility limitations. Found. Orientat. Mobility. New York, NY Am. Found. Blind 461–476.

Blauert, J., 2005. Analysis and synthesis of auditory scenes. Commun. Acoust. 1–25.

Bola, Ł., Zimmermann, M., Mostowski, P., Jednoróg, K., Marchewka, A., Rutkowski, P., Szwed, M., 2017. Task-specific reorganization of the auditory cortex in deaf humans. Proc. Natl. Acad. Sci. 114, E600–E609.

Bolognini, N., Rasi, F., Coccia, M., Ladavas, E., 2005. Visual search improvement in hemianopic patients after audio-visual stimulation. Brain 128, 2830–2842.

Bottari, D., Kekunnaya, R., Hense, M., Troje, N.F., Sourav, S., Röder, B., 2018. Motion processing after sight restoration: No competition between visual recovery and auditory compensation. Neuroimage 167, 284–296.

Bottari, D., Troje, N.F., Ley, P., Hense, M., Kekunnaya, R., Röder, B., 2015. The neural development of the biological motion processing system does not rely on early visual input. cortex 71, 359–367.

Botvinick, M., Cohen, J., 1998. Rubber hands ‘feel’touch that eyes see. Nature 391, 756.

Boyer, E.O., Babayan, B.M., Bevilacqua, F., Noisternig, M., Warusfel, O., Roby-Brami, A., Hanneton, S., Viaud-Delmon, I., 2013. From ear to hand: the role of the auditory-motor loop in pointing to an auditory source. Front. Comput. Neurosci. 7, 26.

Boyer, E.O., Vandervoorde, L., Bevilacqua, F., Hanneton, S., 2015. Touching sounds: perception of the curvature of auditory virtual surfaces, in: 2015 IEEE Virtual Reality (VR). IEEE, pp. 153–154.

Brain, W.R., 1941. Visual orientation with special reference to lesions of the right cerebral hemisphere. Brain A J. Neurol.

Brambring, M., 1982. Language and geographic orientation for the blind. Speech, place, and action 203–218.

Brandwein, A.B., Foxe, J.J., Russo, N.N., Altschuler, T.S., Gomes, H., Molholm, S., 2011. The development of audiovisual multisensory integration across childhood and early adolescence: a high-density electrical mapping study. Cereb. Cortex 21, 1042–1055.

Bremner, A.J., Holmes, N.P., Spence, C., 2008. Infants lost in (peripersonal) space? Trends Cogn. Sci. 12, 298–305.

Bremner, A.J., Lewkowicz, D.J., Spence, C., 2012. Multisensory development. Oxford University Press.

Bremner, A.J., Spence, C., 2008. Unimodal experience constrains while multisensory experiences enrich cognitive construction. Behav. Brain Sci. 31, 335.

Brenner, E., Cornelissen, F., Nuboer, W., 1990. Striking absence of long-lasting effects of early color deprivation on monkey vision. Dev. Psychobiol. J. Int. Soc. Dev. Psychobiol. 23, 441–448.

Brenner, E., Smeets, J.B.J., 2018. Continuously updating one's predictions underlies successful interception. J. Neurophysiol. 120, 3257–3274.

Bullens, J., Iglói, K., Berthoz, A., Postma, A., Rondi-Reig, L., 2010. Developmental time course of the acquisition of sequential egocentric and allocentric navigation strategies. J. Exp. Child Psychol. 107, 337–350.

Burgess, N., 2006. Spatial memory: how egocentric and allocentric combine. Trends Cogn. Sci. 10, 551–557.

Burgess, N., Spiers, H.J., Paleologou, E., 2004. Orientational manoeuvres in the dark: dissociating allocentric and egocentric influences on spatial memory. Cognition 94, 149–166.

Burr, D.C., Morrone, M.C., Vaina, L.M., 1998. Large receptive fields for optic flow detection in humans. Vision Res. 38, 1731–1743.

Campus, C., Sandini, G., Amadeo, M.B., Gori, M., 2019. Stronger responses in the visual cortex of sighted compared to blind individuals during auditory space representation. Sci. Rep. 9, 1–12.

Campus, C., Sandini, G., Morrone, M.C., Gori, M., 2017. Spatial localization of sound elicits early responses from occipital visual cortex in humans. Sci. Rep. 7, 1–12.

Cappagli, G., Cocchi, E., Gori, M., 2015. Auditory and proprioceptive spatial impairments in blind children and adults. Dev. Sci. 20, e12374. https://doi.org/10.1111/desc.12374

Cappagli, G., Finocchietti, S., Baud-Bovy, G., Cocchi, E., Gori, M., 2017. Multisensory rehabilitation training improves spatial perception in totally but not partially visually deprived children. Front. Integr. Neurosci. 11. https://doi.org/10.3389/fnint.2017.00029

Cappagli, G., Finocchietti, S., Cocchi, E., Giammari, G., Zumiani, R., Cuppone, A.V., Baud-Bovy, G., Gori, M., 2019. Audio motor training improves mobility and spatial cognition in visually impaired children. Sci. Rep. 9, 1–9.

Cappagli, G., Gori, M., 2019. The role of vision on spatial competence, in: Visual Impairment and Blindness-What We Know and What We Have to Know. IntechOpen.

Cappagli, G., Gori, M., 2016. Auditory spatial localization: developmental delay in children with visual impairments. Res. Dev. Disabil. 53, 391–398.

Caraiman, S., Morar, A., Owczarek, M., Burlacu, A., Rzeszotarski, D., Botezatu, N., Herghelegiu, P., Moldoveanu, F., Strumillo, P., Moldoveanu, A., 2017. Computer Vision for the Visually Impaired: The Sound of Vision System, in: Proceedings - 2017 IEEE International Conference on Computer Vision Workshops, ICCVW 2017. Institute of Electrical and Electronics Engineers Inc., pp. 1480–1489. https://doi.org/10.1109/ICCVW.2017.175

Carello, C., Anderson, K.L., Kunkler-Peck, A.J., 1998. Perception of object length by sound. Psychol. Sci. 9, 211–214.

Cattaneo, Z., Vecchi, T., Cornoldi, C., Mammarella, I., Bonino, D., Ricciardi, E., Pietrini, P., 2008. Imagery and spatial processes in blindness and visual impairment. Neurosci. Biobehav. Rev. 32, 1346–1360. https://doi.org/https://doi.org/10.1016/j.neubiorev.2008.05.002

Cholewiak, R.W., Brill, J.C., Schwab, A., 2004. Vibrotactile localization on the abdomen: Effects of place and space. Percept. Psychophys. 66, 970–987. https://doi.org/10.3758/BF03194989

Clark, A., 2006. That lonesome whistle: a puzzle for the sensorimotor model of perceptual experience. Analysis 66, 22–25.

Clifton, R.K., 1992. The development of spatial hearing in human infants.

Clifton, R.K., Perris, E.E., Bullinger, A., 1991. Infants' perception of auditory space. Dev. Psychol. 27, 187.

Colenbrander, A., 2010. Assessment of functional vision and its rehabilitation. Acta Ophthalmol. 88, 163–173.

Collignon, O., De Volder, A.G., 2009. Further evidence that congenitally blind participants react faster to auditory and tactile spatial targets. Can. J. Exp. Psychol. Can. Psychol.

expérimentale 63, 287.

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

Colonius, H., Diederich, A., 2004. Multisensory interaction in saccadic reaction time: a time-window-of-integration model. J. Cogn. Neurosci. 16, 1000–1009.

Cornoldi, C., Cortesi, A., Preti, D., 1991. Individual differences in the capacity limitations of visuospatial short-term memory: Research on sighted and totally congenitally blind people. Mem. Cognit. 19, 459–468.

Csapó, Á., Wersényi, G., Nagy, H., Stockman, T., 2015. A survey of assistive technologies and applications for blind users on mobile platforms: a review and foundation for research. J. Multimodal User Interfaces 9, 275–286.

Cuppone, A.V., Cappagli, G., Gori, M., 2018. Audio feedback associated with body movement enhances audio and somatosensory spatial representation. Front. Integr. Neurosci. 12, 37.

Cuturi, L.F., Aggius-Vella, E., Campus, C., Parmiggiani, A., Gori, M., 2016. From science to technology: Orientation and mobility in blind children and adults. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2016.08.019

Danilova, M. V, Bondarko, V.M., 2007. Foveal contour interactions and crowding effects at the resolution limit of the visual system. J. Vis. 7, 25.

Dehaene, S., 2005. Evolution of human cortical circuits for reading and arithmetic: The "neuronal recycling" hypothesis. From monkey brain to Hum. brain 133–157.

Dehaene, S., Cohen, L., 2007. Cultural recycling of cortical maps. Neuron 56, 384–398.

Deneve, S., Pouget, A., 2004. Bayesian multisensory integration and cross-modal spatial links. J. Physiol. 98, 249–258.

Diederich, A., Colonius, H., Bockhorst, D., Tabeling, S., 2003. Visual-tactile spatial interaction in saccade generation. Exp. Brain Res. 148, 328–337.

Doucet, M.-E., Guillemot, J.-P., Lassonde, M., Gagné, J.-P., Leclerc, C., Lepore, F., 2005. Blind subjects process auditory spectral cues more efficiently than sighted individuals. Exp. brain Res. 160, 194–202.

Dunai, L., Peris-Fajarnés, G., Lluna, E., Defez, B., 2013. Sensory navigation device for blind people. J. Navig. 66, 349–362.

Eckert, M., Blex, M., Friedrich, C.M., 2018. Object detection featuring 3D audio localization for Microsoft HoloLens, in: Proc. 11th Int. Joint Conf. on Biomedical Engineering

Systems and Technologies. pp. 555–561.

Eimer, M., 2014. The neural basis of attentional control in visual search. Trends Cogn. Sci. 18, 526–535.

Eimer, M., 2004. Multisensory integration: how visual experience shapes spatial perception. Curr. Biol. 14, R115–R117.

Elbert, T., Sterr, A., Rockstroh, B., Pantev, C., Müller, M.M., Taub, E., 2002. Expansion of the tonotopic area in the auditory cortex of the blind. J. Neurosci. 22, 9941–9944.

Elder, J., Zucker, S., 1993. The effect of contour closure on the rapid discrimination of two-dimensional shapes. Vision Res. 33, 981–991.

Ellemberg, D., Lewis, T.L., Maurer, D., Lui, C.H., Brent, H.P., 1999. Spatial and temporal vision in patients treated for bilateral congenital cataracts. Vision Res. 39, 3480–3489.

Erdogan, G., Jacobs, R.A., 2017. Visual shape perception as Bayesian inference of 3D object-centered shape representations. Psychol. Rev. 124, 740.

Ernst, M.O., Banks, M.S., 2002. Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415, 429–433.

Ertan, S., Lee, C., Willets, A., Tan, H., Pentland, A., 1998. A wearable haptic navigation guidance system, in: International Symposium on Wearable Computers, Digest of Papers. IEEE Computer Society, pp. 164–165. https://doi.org/10.1109/ISWC.1998.729547

Fazzi, E., Lanners, J., Ferrari-Ginevra, O., Achille, C., Luparia, A., Signorini, S., Lanzi, G., 2002. Gross motor development and reach on sound as critical tools for the development of the blind child. Brain Dev. 24, 269–275.

Feinkohl, A., Locke, S.M., Leung, J., Carlile, S., 2014. The effect of velocity on auditory representational momentum. J. Acoust. Soc. Am. 136, EL20–EL25.

Filimon, F., 2015. Are all spatial reference frames egocentric? Reinterpreting evidence for allocentric, object-centered, or world-centered reference frames. Front. Hum. Neurosci. 9, 648.

Finocchietti, S., Cappagli, G., Baud-Bovy, G., Magnusson, C., Caltenco, H., Wilson, G., Brewster, S., Rogge, A.-K., Röder, B., Cocchi, E., 2015a. ABBI, a new technology for sensory-motor rehabilitation of visual impaired people, in: International Conference on Enabling Access for Persons with Visual Impairment. pp. 80–84.

Finocchietti, S., Cappagli, G., Gori, M., 2017. Auditory spatial recalibration in congenital blind individuals. Front. Neurosci. 11, 76.

Finocchietti, S., Cappagli, G., Gori, M., 2015b. Encoding audio motion: spatial impairment in early blind individuals. Front. Psychol. 6, 1357.

Finocchietti, S., Cappagli, G., Porquis, L. Ben, Baud-Bovy, G., Cocchi, E., Gori, M., 2015c. Evaluation of the Audio Bracelet for Blind Interaction for improving mobility and spatial cognition in early blind children-A pilot study, in: 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, pp. 7998–8001.

Flanagan, J.R., Beltzner, M.A., 2000. Independence of perceptual and sensorimotor predictions in the size–weight illusion. Nat. Neurosci. 3, 737–741.

Foley, R.T., Whitwell, R.L., Goodale, M.A., 2015. The two-visual-systems hypothesis and the perspectival features of visual experience. Conscious. Cogn. 35, 225–233.

Foulke, E., 1982. Perception,cognition,and mobility of blind pedestrians. Spat. Orientat. Dev. Physiol. Found. York, NY Acad. Press. ed. M. Potegal 55–76.

Foxe, J.J., 2009. Multisensory integration: frequency tuning of audio-tactile integration. Curr. Biol. 19, R373–R375.

Foxe, J.J., Morocz, I.A., Murray, M.M., Higgins, B.A., Javitt, D.C., Schroeder, C.E., 2000. Multisensory auditory-somatosensory interactions in early cortical processing revealed by high-density electrical mapping. Brain Res. Cogn. Brain Res. 10, 77–83.

Foxe, J.J., Wylie, G.R., Martinez, A., Schroeder, C.E., Javitt, D.C., Guilfoyle, D., Ritter, W., Murray, M.M., 2002. Auditory-somatosensory multisensory processing in auditory association cortex: an fMRI study. J. Neurophysiol. 88, 540–543.

Fraiberg, S., 1977. Congenital sensory and motor deficits and ego formation. Annu. Psychoanal. 5, 169–194.

Fraiberg, S., Siegel, B.L., Gibson, R., 1966. The role of sound in the search behavior of a blind infant. Psychoanal. Study Child 21, 327–357.

Frassinetti, F., Bolognini, N., Bottari, D., Bonora, A., Ladavas, E., 2005. Audiovisual integration in patients with visual deficit. J. Cogn. Neurosci. 17, 1442–1452.

Freyd, J.J., Finke, R.A., 1984. Representational momentum. J. Exp. Psychol. Learn. Mem. Cogn. 10, 126.

Fristot, V., Boucheteil, J., Granjon, L., Pellerin, D., Alleysson, D., 2012. Depth—Melody substitution, in: 2012 Proceedings of the 20th European Signal Processing Conference (EUSIPCO). IEEE, pp. 1990–1994.

Fröhlich, F.W., 1923. Über die Messung der Empfindungszeit [Measuring the time of sensation]. Zeitschrift für Sinnesphysiologie 54, 58–78.

Galati, G., Pelle, G., Berthoz, A., Committeri, G., 2010. Multiple reference frames used by the human brain for spatial perception and memory. Exp. brain Res. 206, 109–120.

Gardner, J.L., Merriam, E.P., Movshon, J.A., Heeger, D.J., 2008. Maps of visual space in human occipital cortex are retinotopic, not spatiotopic. J. Neurosci. 28, 3988–3999.

Garrigan, P., 2012. The effect of contour closure on shape recognition. Perception 41, 221–235.

Gaunet, F., Ittyerah, M., Rossetti, Y., 2007. Pointing at targets by children with congenital and transient blindness. Exp. brain Res. 178, 167–179.

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

Geldart, S., Mondloch, C.J., Maurer, D., De Schonen, S., Brent, H.P., 2002. The effect of early visual deprivation on the development of face processing. Dev. Sci. 5, 490–501.

Gescheider, G.A., Bolanowski, S.J., Pope, J. V, Verrillo, R.T., 2002. A four-channel analysis of the tactile sensitivity of the fingertip: frequency selectivity, spatial summation, and temporal summation. Somatosens. Mot. Res. 19, 114–124.

Getzmann, S., 2005a. Shifting the onset of a moving sound source: A Fröhlich effect in spatial hearing. Hear. Res. 210, 104–111.

Getzmann, S., 2005b. Representational momentum in spatial hearing does not depend on eye movements. Exp. Brain Res. 165, 229–238.

Getzmann, S., Lewald, J., Guski, R., 2004. Representational momentum in spatial hearing. Perception 33, 591–599.

Giudice, N.A., 2018. Navigating without vision: principles of blind spatial cognition, in: Handbook of Behavioral and Cognitive Geography. Edward Elgar Publishing.

Giudice, N.A., Betty, M.R., Loomis, J.M., 2011. Functional equivalence of spatial images from touch and vision: evidence from spatial updating in blind and sighted individuals. J. Exp. Psychol. Learn. Mem. Cogn. 37, 621.

Golomb, J.D., Chun, M.M., Mazer, J.A., 2008. The native coordinate system of spatial attention is retinotopic. J. Neurosci. 28, 10654–10662.

González-Mora, J.L., R Odríguez-Hernández, A., Rodríguez-Ramos, L.F., Dfaz-Saco, L., Sosa, N., 1999. Development of a new space perception system for blind people, based on the creation of a virtual acoustic space, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). Springer Verlag, pp. 321–330. https://doi.org/10.1007/BFb0100499

González-Mora, J.L., Rodriguez-Hernandez, A., Burunat, E., Martin, F., Castellano, M.A., 2006. Seeing the world by hearing: Virtual Acoustic Space (VAS) a new space perception system for blind people., in: 2006 2nd International Conference on Information & Communication Technologies. IEEE, pp. 837–842.

Gori, M., 2015. Multisensory integration and calibration in children and adults with and without sensory and motor disabilities. Multisens. Res. 28, 1–2, 71–99.

Gori, Monica, 2015. Multisensory integration and calibration in children and adults with and without sensory and motor disabilities. Multisens. Res. 28, 71–99. https://doi.org/10.1163/22134808-00002478

Gori, M., Amadeo, M.B., Campus, C., 2020a. Spatial metric in blindness: behavioural and cortical processing. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2019.12.031

Gori, M., Amadeo, M.B., Campus, C., 2020b. Temporal cues trick the visual and auditory cortices mimicking spatial cues in blind individuals. Hum. Brain Mapp. 41, 2077–2091. https://doi.org/10.1002/hbm.24931

Gori, M., Amadeo, M.B., Campus, C., 2018. Temporal cues influence space estimations in visually impaired individuals. IScience 6, 319–326.

Gori, M., Bollini, A., Maviglia, A., Amadeo, M.B., Tonelli, A., Crepaldi, M., Campus, C., 2019. Msi caterpillar: An effective multisensory system to evaluate spatial body representation, in: 2019 IEEE International Symposium on Medical Measurements and Applications (MeMeA). IEEE, pp. 1–6.

Gori, M., Cappagli, G., Baud-Bovy, G., Finocchietti, S., 2017. Shape perception and navigation in blind adults. Front. Psychol. 8. https://doi.org/10.3389/fpsyg.2017.00010

Gori, M., Cappagli, G., Tonelli, A., Baud-Bovy, G., Finocchietti, S., 2016. Devices for visually impaired people: High technological devices with low user acceptance and no adaptability for children. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2016.06.043

Gori, M., Giuliana, L., Sandini, G., Burr, D., 2012a. Visual size perception and haptic calibration during development. Dev. Sci. 15, 854–862.

Gori, M., Mazzilli, G., Sandini, G., Burr, D., 2011. Cross-sensory facilitation reveals neural interactions between visual and tactile motion in humans. Front. Psychol. 2, 55.

Gori, M., Sandini, G., Burr, D., 2012b. Development of visuo-auditory integration in space and time. Front. Integr. Neurosci. 6, 77.

Gori, M., Sandini, G., Martinoli, C., Burr, D., 2010. Poor Haptic Orientation Discrimination in Nonsighted Children May Reflect Disruption of Cross-Sensory Calibration. Curr. Biol. 20, 223–225. https://doi.org/10.1016/j.cub.2009.11.069

Gori, M., Sandini, G., Martinoli, C., Burr, D.C., 2014. Impairment of auditory spatial localization in congenitally blind human subjects. Brain 137, 288–293.

Gori, M., Sciutti, A., Jacono, M., Sandini, G., Morrone, C., Burr, D., 2013. Long integration time for accelerating and decelerating visual, tactile and visuo-tactile stimuli. Multisens. Res. 26, 53–68.

Gougoux, F., Lepore, F., Lassonde, M., Voss, P., Zatorre, R.J., Belin, P., 2004. Pitch discrimination in the early blind. Nature 430, 309. https://doi.org/10.1038/430309a

Gougoux, F., Zatorre, R.J., Lassonde, M., Voss, P., Lepore, F., 2005. A functional neuroimaging study of sound localization: Visual cortex activity predicts performance in early-blind individuals. PLoS Biol. 3, 0324–0333. https://doi.org/10.1371/journal.pbio.0030027

Grasso, P.A., Làdavas, E., Bertini, C., 2016. Compensatory recovery after multisensory stimulation in hemianopic patients: behavioral and neurophysiological components. Front. Syst. Neurosci. 10, 45.

Hadad, B., Maurer, D., Lewis, T.L., 2012. Sparing of sensitivity to biological motion but not of global motion after early visual deprivation. Dev. Sci. 15, 474–481.

Haigh, A., Brown, D.J., Meijer, P., Proulx, M.J., 2013. How well do you see what you hear? The acuity of visual-to-auditory sensory substitution. Front. Psychol. https://doi.org/10.3389/fpsyg.2013.00330

Hall, E.T., 1966. The hidden dimension. Garden City, NY: Doubleday.

Hallemans, A., Ortibus, E., Truijen, S., Meire, F., 2011. Development of independent locomotion in children with a severe visual impairment. Res. Dev. Disabil. 32, 2069–2074. https://doi.org/10.1016/j.ridd.2011.08.017

Hamilton-Fletcher, G., Obrist, M., Watten, P., Mengucci, M., Ward, J., 2016. “I always wanted to see the night sky”: Blind user preferences for sensory substitution devices, in: Conference on Human Factors in Computing Systems - Proceedings. Association for

Computing Machinery, pp. 2162–2174. https://doi.org/10.1145/2858036.2858241

Hamilton-Fletcher, G., Ward, J., 2013. Representing colour through hearing and touch in sensory substitution devices. Multisens. Res. 26, 503–532.

Hannagan, T., Amedi, A., Cohen, L., Dehaene-Lambertz, G., Dehaene, S., 2015. Origins of the specialization for letters and numbers in ventral occipitotemporal cortex. Trends Cogn. Sci. 19, 374–382.

Harris, M.A., Wiener, J.M., Wolbers, T., 2012. Aging specifically impairs switching to an allocentric navigational strategy. Front. Aging Neurosci. 4, 29.

Hart, R.A., Moore, G.T., 1973. The development of spatial cognition: A review. AldineTransaction.

Hayes, A.E., Freyd, J.J., 2002. Representational momentum when attention is divided. Vis. cogn. 9, 8–27.

Hermer, L., Spelke, E., 1996. Modularity and development: The case of spatial reorientation. Cognition 61, 195–232.

Hermer, L., Spelke, E.S., 1994. A geometric process for spatial reorientation in young children. Nature 370, 57–59.

Hollins, M., Kelley, E.K., 1988. Spatial updating in blind and sighted people. Percept. Psychophys. 43, 380–388.

Holmes, N.P., Spence, C., 2004. The body schema and multisensory representation (s) of peripersonal space. Cogn. Process. 5, 94–105.

Hötting, K., Röder, B., 2004. Hearing Cheats Touch, but Less in Congenitally Blind Than in Sighted Individuals. Psychol. Sci. 15, 60–64. https://doi.org/10.1111/j.0963-7214.2004.01501010.x

Houwen, S., Hartman, E., Visscher, C., 2009. Physical activity and motor skills in children with and without visual impairments. Med. Sci. Sports Exerc. 41, 103–109.

https://www.abbiproject.eu/ [WWW Document], n.d.

Hubbard, T.L., 2005. Representational momentum and related displacements in spatial memory: A review of the findings. Psychon. Bull. Rev. 12, 822–851.

Hüg, M.X., Arias, C., Tommasini, F.C., Ramos, O.A., 2014. Auditory localization and precedence effect: an exploratory study in infants and toddlers with visual impairment and normal vision. Res. Dev. Disabil. 35, 2015–2025.

Huttenlocher, J., Presson, C.C., 1973. Mental rotation and the perspective problem. Cogn.

Psychol. 4, 277–299.

Hyvärinen, L., 1995. Considerations in evaluation and treatment of the child with low vision. Am. J. Occup. Ther. 49, 891–897.

Iachini, T., Ruggiero, G., Ruotolo, F., 2014. Does blindness affect egocentric and allocentric frames of reference in small and large scale spaces? Behav. Brain Res. 273, 73–81. https://doi.org/10.1016/j.bbr.2014.07.032

Jacobson, R.D., 1998. Cognitive mapping without sight: Four preliminary studies of spatial learning. J. Environ. Psychol. 18, 289–305.

Jones, L.A., Nakamura, M., Lockyer, B., 2004. Development of a tactile vest, in: Proceedings - 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS. pp. 82–89. https://doi.org/10.1109/HAPTIC.2004.1287181

Kalia, A., Lesmes, L.A., Dorr, M., Gandhi, T., Chatterjee, G., Ganesh, S., Bex, P.J., Sinha, P., 2014. Development of pattern vision following early and extended blindness. Proc. Natl. Acad. Sci. 111, 2035–2039.

Kappers, A.M.L., 1999. Large systematic deviations in the haptic perception of parallelity. Perception 28, 1001–1012.

Kappers, A.M.L., Koenderink, J.J., 1999. Haptic perception of spatial relations. Perception 28, 781–795.

Keniston, L.P., Henderson, S.C., Meredith, M.A., 2010. Neuroanatomical identification of crossmodal auditory inputs to interneurons in somatosensory cortex. Exp. brain Res. 202, 725–731.

Kerzel, D., 2003. Mental extrapolation of target position is strongest with weak motion signals and motor responses. Vision Res. 43, 2623–2635.

Kerzel, D., Gegenfurtner, K.R., 2004. Spatial distortions and processing latencies in the onset repulsion and Fröhlich effects. Vision Res. 44, 577–590.

King, A.J., 2015. Crossmodal plasticity and hearing capabilities following blindness. Cell Tissue Res. 361, 295–300.

King, A.J., 2009. Visual influences on auditory spatial learning. Philos. Trans. R. Soc. B Biol. Sci. 364, 331–339.

King, A.J., Carlile, S., 1993. Changes induced in the representation of auditory space in the superior colliculus by rearing ferrets with binocular eyelid suture. Exp. Brain Res. 94, 444–455.

King, A.J., Hutchings, M.E., Moore, D.R., Blakemore, C., 1988. Developmental plasticity in the visual and auditory representations in the mammalian superior colliculus. Nature 332, 73–76.

King, A.J., Parsons, C.H., 1999. Improved auditory spatial acuity in visually deprived ferrets. Eur. J. Neurosci. 11, 3945–3956.

Kirschfeld, K., Kammer, T., 1999. The Fröhlich effect: A consequence of the interaction of visual focal attention and metacontrast. Vision Res. 39, 3702–3709.

Klatzky, R.L., 1999. Path completion after haptic exploration without vision: Implications for haptic spatial representations. Percept. Psychophys. 61, 220–235.

Klatzky, R.L., 1998. Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections, in: Spatial Cognition. Springer, pp. 1–17.

Knudsen, E.I., Brainard, M.S., 1991. Visual instruction of the neural map of auditory space in the developing optic tectum. Science (80-.). 253, 85–87.

Kolarik, Andrew J., Cirstea, S., Pardhan, S., 2013. Evidence for enhanced discrimination of virtual auditory distance among blind listeners using level and direct-to-reverberant cues. Exp. Brain Res. 224, 623–633. https://doi.org/10.1007/s00221-012-3340-0

Kolarik, Andrew J, Cirstea, S., Pardhan, S., Moore, B.C., 2013. An assessment of virtual auditory distance judgments among blind and sighted listeners, in: Proceedings of Meetings on Acoustics ICA2013. Acoustical Society of America, p. 50043.

Kolarik, A.J., Cirstea, S., Pardhan, S., Moore, B.C.J., 2014. A summary of research investigating echolocation abilities of blind and sighted humans. Hear. Res. 310, 60–68.

Kolarik, A.J., Moore, B.C.J., Zahorik, P., Cirstea, S., Pardhan, S., 2016. Auditory distance perception in humans: a review of cues, development, neuronal bases, and effects of sensory loss. Attention, Perception, Psychophys. 78, 373–395.

Kolarik, A.J., Pardhan, S., Cirstea, S., Moore, B.C.J., 2017. Auditory spatial representations of the world are compressed in blind humans. Exp. Brain Res. 235, 597–606. https://doi.org/10.1007/s00221-016-4823-1

Komeilipoor, N., Rodger, M.W.M., Cesari, P., Craig, C.M., 2015. Movement and perceptual strategies to intercept virtual sound sources. Front. Neurosci. 9, 149.

Korte, M., Rauschecker, J.P., 1993. Auditory spatial tuning of cortical neurons is sharpened in cats with early blindness. J. Neurophysiol. 70, 1717–1721.

Koustriava, E., Papadopoulos, K., 2012. Are there relationships among different spatial skills of individuals with blindness? Res. Dev. Disabil. 33, 2164–2176.

Koustriava, E., Papadopoulos, K., 2010. Mental rotation ability of individuals with visual impairments. J. Vis. Impair. Blind. 104, 570–575.

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J.H., Miner, N., Neuhoff, J., 2010. Sonification report: Status of the field and research agenda.

Landau, B., Spelke, E., Gleitman, H., 1984. Spatial knowledge in a young blind child. Cognition 16, 225–260.

Laurienti, P.J., Kraft, R.A., Maldjian, J.A., Burdette, J.H., Wallace, M.T., 2004. Semantic congruence is a critical factor in multisensory behavioral performance. Exp. brain Res. 158, 405–414.

Lazzouni, L., Lepore, F., 2014. Compensatory plasticity: time matters. Front. Hum. Neurosci. 8, 340.

Le Grand, R., Mondloch, C.J., Maurer, D., Brent, H.P., 2001. Early visual experience and face processing. Nature 410, 890.

Lenay, C., Gapenne, O., Hanneton, S., Marque, C., Genouëlle, C., 2003. Sensory substitution: Limits and perspectives. Touching for knowing 275–292.

Lepore, N., Shi, Y., Lepore, F., Fortin, M., Voss, P., Chou, Y.-Y., Lord, C., Lassonde, M., Dinov, I.D., Toga, A.W., 2009. Pattern of hippocampal shape and volume differences in blind subjects. Neuroimage 46, 949–957.

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

Levitt, J.B., Lund, J.S., 1997. Contrast dependence of contextual effects in primate visual cortex. Nature 387, 73–76.

Levtzion-Korach, O., Tennenbaum, A., Schnitzer, R., Ornoy, A., 2000. Early motor development of blind children. J. Paediatr. Child Health 36, 226–229.

Lew, A.R., Bremner, J.G., Lefkovitch, L.P., 2000. The Development of Relational Landmark Use in Six-to Twelve-Month-Old Infants in a Spatial Orientation Task. Child Dev. 71, 1179–1190.

Lewald, J., 2013. Exceptional ability of blind humans to hear sound motion: implications for the emergence of auditory space. Neuropsychologia 51, 181–186.

Lewald, J., 2007. More accurate sound localization induced by short-term light deprivation. Neuropsychologia 45, 1215–1222.

Lewald, J., 2002. Vertical sound localization in blind humans. Neuropsychologia 40, 1868–1872.

Lewis, T.L., Ellemberg, D., Maurer, D., Wilkinson, F., Wilson, H.R., Dirks, M., Brent, H.P., 2002. Sensitivity to global form in glass patterns after early visual deprivation in humans. Vision Res. 42, 939–948.

Lewis, T.L., Maurer, D., 2005. Multiple sensitive periods in human visual development: evidence from visually deprived children. Dev. Psychobiol. J. Int. Soc. Dev. Psychobiol. 46, 163–183.

Lewkowicz, D.J., 2008. Perception of dynamic and static audiovisual sequences in 3-and 4-month-old infants. Child Dev. 79, 1538–1554.

Li, C.-Y., Lei, J.-J., Yao, H.-S., 1999. Shift in speed selectivity of visual cortical neurons: a neural basis of perceived motion contrast. Proc. Natl. Acad. Sci. 96, 4052–4056.

Litovsky, R.Y., Clifton, R.K., 1992. Use of sound-pressure level in auditory distance discrimination by 6-month-old infants and adults. J. Acoust. Soc. Am. 92, 794–802.

Lomber, S.G., Meredith, M.A., Kral, A., 2010. Cross-modal plasticity in specific auditory cortices underlies visual compensations in the deaf. Nature Neuroscience. Vertebr. eye its Adapt. Radiat. 13(11), 1421–1427.

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. J. Exp. Psychol. Gen. 122, 73.

Lourenco, S.F., Huttenlocher, J., 2008. The representation of geometric cues in infancy. Infancy 13, 103–127.

Macaluso, E., Maravita, A., 2010. The representation of space near the body through touch and vision. Neuropsychologia 48, 782–795.

MacSweeney, M., Cardin, V., 2015. What is the function of auditory cortex without auditory input? Brain 138, 2468–2470.

Maddox, R.K., Atilgan, H., Bizley, J.K., Lee, A.K.C., 2015. Auditory selective attention is enhanced by a task-irrelevant temporally coherent visual stimulus in human listeners. Elife 4, e04995.

Maidenbaum, S., Abboud, S., Amedi, A., 2014. Sensory substitution: Closing the gap between basic research and widespread practical visual rehabilitation. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2013.11.007

Marchand, S., Arsenault, P., 2002. Spatial summation for pain perception: interaction of inhibitory and excitatory mechanisms. Pain 95, 201–206.

Markowitz, S.N., 2016. State-of-the-art: low vision rehabilitation. Can. J. Ophthalmol. 51, 59–66.

Martolini, C., Cappagli, G., Campus, C., Gori, M., 2020a. Shape recognition with sounds: improvement in sighted individuals after audio–motor training. Multisens. Res. 33, 417–431.

Martolini, C., Cappagli, G., Luparia, A., Signorini, S., Gori, M., 2020b. The impact of vision loss on allocentric spatial coding. Front. Neurosci. 14, 565.

Martolini, C., Cuppone, A. V, Cappagli, G., Finocchietti, S., Maviglia, A., Gori, M., 2018. ABBI-K: a novel tool for evaluating spatial and motor abilities in visually impaired children, in: 2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA). IEEE, pp. 1–6.

Mateeff, S., Hohnsbein, J., Noack, T., 1985. Dynamic visual capture: apparent auditory motion induced by a moving visual target. Perception 14, 721–727.

Maurer, D., Lewis, T.L., Mondloch, C.J., 2005. Missing sights: consequences for visual cognitive development. Trends Cogn. Sci. 9, 144–151.

Maye, A., Engel, A.K., 2011. A discrete computational model of sensorimotor contingencies for object perception and control of behavior, in: 2011 IEEE International Conference on Robotics and Automation. IEEE, pp. 3810–3815.

McKyton, A., Ben-Zion, I., Doron, R., Zohary, E., 2015. The limits of shape recognition following late emergence from blindness. Curr. Biol. 25, 2373–2378.

Meijer, P.B.L., 1992. An Experimental System for Auditory Image Representations. IEEE Trans. Biomed. Eng. 39, 112–121. https://doi.org/10.1109/10.121642

Merabet, L.B., Pascual-Leone, A., 2010. Neural reorganization following sensory loss: the opportunity of change. Nat. Rev. Neurosci. 11, 44–52.

Meredith, M.A., Allman, B.L., Keniston, L.P., Clemo, H.R., 2009. Auditory influences on non-auditory cortices. Hear. Res. 258, 64–71.

Millar, S., 1994. Understanding and representing space: Theory and evidence from studies with blind and sighted children. Clarendon Press/Oxford University Press.

Millar, S., 1985. Movement cues and body orientation in recall of locations by blind and sighted children. Q. J. Exp. Psychol. Sect. A 37, 257–279.

Millar, S., 1981. Self-referent and movement cues in coding spatial location by blind and sighted children. Perception 10, 255–264.

Millar, S., 1976. Spatial representation by blind and sighted children. J. Exp. Child Psychol. 21, 460–479.

Millar, S., Ittyerah, M., 1992. Movement imagery in young and congenitally blind children: Mental practice without visuo-spatial information. Int. J. Behav. Dev. 15, 125–146.

Miller, J., 1982. Divided attention: Evidence for coactivation with redundant signals. Cogn. Psychol. 14, 247–279.

Milner, A.D., Goodale, M.A., 1995. The visual brain in action. Oxford Psychol. Press.

Milner, P.M., 1974. A model for visual shape recognition. Psychol. Rev. 81, 521.

Molholm, S., Ritter, W., Murray, M.M., Javitt, D.C., Schroeder, C.E., Foxe, J.J., 2002. Multisensory auditory–visual interactions during early sensory processing in humans: a high-density electrical mapping study. Cogn. brain Res. 14, 115–128.

Morrongiello, B.A., Fenwick, K.D., Chance, G., 1998. Crossmodal learning in newborn infants: Inferences about properties of auditory-visual events. Infant Behav. Dev. 21, 543–553.

Muir, D., Field, J., 1979. Newborn infants orient to sounds. Child Dev. 431–436.

Murray, M.M., Molholm, S., Michel, C.M., Heslenfeld, D.J., Ritter, W., Javitt, D.C., Schroeder, C.E., Foxe, J.J., 2005. Grabbing your ear: rapid auditory–somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment. Cereb. cortex 15, 963–974.

Müsseler, J., Aschersleben, G., 1998. Localizing the first position of a moving stimulus: The Fröhlich effect and an attention-shifting explanation. Percept. Psychophys. 60, 683–695.

Müsseler, J., Stork, S., Kerzel, D., 2002. Comparing mislocalizations with moving stimuli: The Fröhlich effect, the flash-lag, and representational momentum. Vis. cogn. 9, 120–138.

Nadel, L., Hardt, O., 2004. The spatial brain. Neuropsychology 18, 473.

Nardini, M., Burgess, N., Breckenridge, K., Atkinson, J., 2006. Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. Cognition 101, 153–172.

Nardini, M., Jones, P., Bedford, R., Braddick, O., 2008. Development of cue integration in human navigation. Curr. Biol. 18, 689–693.

Nardini, M., Thomas, R.L., Knowland, V.C.P., Braddick, O.J., Atkinson, J., 2009. A viewpoint-independent process for spatial reorientation. Cognition 112, 241–248.

Nau, A., Bach, M., Fisher, C., 2013. Clinical tests of ultra-low vision used to evaluate rudimentary visual perceptions enabled by the BrainPort vision device. Transl. Vis. Sci. Technol. 2, 1.

Nelson, J.S., Baud-Bovy, G., Smeets, J.B.J., Brenner, E., 2019. Accuracy of intercepting moving tactile targets. Perception 48, 685–701.

Newcombe, N., Huttenlocher, J., 2003. Making space: The development of spatial representation and reasoning. MIT Press.

Newcombe, N., Huttenlocher, J., Drummey, A.B., Wiley, J.G., 1998. The development of spatial location coding: Place learning and dead reckoning in the second and third years. Cogn. Dev. 13, 185–200.

Newcombe, N., Huttenlocher, J., Learmonth, A., 1999. Infants' coding of location in continuous space. Infant Behav. Dev. 22, 483–510.

Newell, F.N., Woods, A.T., Mernagh, M., Bülthoff, H.H., 2005. Visual, haptic and crossmodal recognition of scenes. Exp. Brain Res. 161, 233–242.

Newport, R., Rabb, B., Jackson, S.R., 2002. Noninformative vision improves haptic spatial perception. Curr. Biol. 12, 1661–1664.

Noordzij, M.L., Zuidhoek, S., Postma, A., 2007. The influence of visual experience on visual and spatial imagery. Perception 36, 101–112.

Noory, B., Herzog, M.H., Ogmen, H., 2015. Spatial properties of non-retinotopic reference frames in human vision. Vision Res. 113, 44–54.

O'Regan, J.K., Noë, A., 2001. A sensorimotor account of vision and visual consciousness. Behav. Brain Sci. 24, 939–973. https://doi.org/10.1017/S0140525X01000115

Ochaíta, E., Huertas, J.A., 1993. Spatial representation by persons who are blind: A study of the effects of learning and development. J. Vis. Impair. Blind. 87, 37–41.

Overman, W.H., Pate, B.J., Moore, K., Peuster, A., 1996. Ontogeny of place learning in children as measured in the radial arm maze, Morris search task, and open field task. Behav. Neurosci. 110, 1205.

Papadopoulos, K., Koustriava, E., 2011. The impact of vision in spatial coding. Res. Dev. Disabil. 32, 2084–2091.

Pascual-Leone, A., Hamilton, R.B.T., 2001. The metamodal organization of the brain, in: Vision: From Neurons to Cognition. Elsevier, pp. 427–445. https://doi.org/https://doi.org/10.1016/S0079-6123(01)34028-1

Pasqualotto, A., Newell, F.N., 2007. The role of visual experience on the representation and updating of novel haptic scenes. Brain Cogn. 65, 184–194.

Pasqualotto, A., Proulx, M.J., 2012. The role of visual experience for the neural basis of spatial cognition. Neurosci. Biobehav. Rev. https://doi.org/10.1016/j.neubiorev.2012.01.008

Pasqualotto, A., Spiller, M.J., Jansari, A.S., Proulx, M.J., 2013. Visual experience facilitates allocentric spatial representation. Behav. Brain Res. 236, 175–179. https://doi.org/10.1016/j.bbr.2012.08.042

Passamonti, C., Bertini, C., Làdavas, E., 2009. Audio-visual stimulation improves oculomotor patterns in patients with hemianopia. Neuropsychologia 47, 546–555.

Pavani, F., Bottari, D., 2011. Visual abilities in individuals with profound deafness: A critical review, in: The Neural Bases of Multisensory Processes. CRC Press, pp. 423–447.

Peelen, M. V, He, C., Han, Z., Caramazza, A., Bi, Y., 2014. Nonvisual and visual object shape representations in occipitotemporal cortex: evidence from congenitally blind and sighted adults. J. Neurosci. 34, 163–170.

Penrod, W.M., Petrosko, J., 2003. Spatial organization skills of the blind in large outdoor places. RE view 34, 155.

Pérez-Pereira, M., Conti-Ramsden, G., 2005. Do blind children show autistic features. Autism Blind. Res. reflections 99–127.

Perris, E.E., Clifton, R.K., 1988. Reaching in the dark toward sound as a measure of auditory localization in infants. Infant Behav. Dev. 11, 473–491.

Perrott, D.R., Musicant, A.D., 1977. Minimum auditory movement angle: Binaural localization of moving sound sources. J. Acoust. Soc. Am. 62, 1463–1466.

Petrus, E., Isaiah, A., Jones, A.P., Li, D., Wang, H., Lee, H.-K., Kanold, P.O., 2014. Crossmodal induction of thalamocortical potentiation leads to enhanced information processing in the auditory cortex. Neuron 81, 664–673.

Piaget, J., Inhelder, B., 1967. La psychologie de l’enfant. Que sais-je.

Piaget, J., Inhelder, B., Szeminska, A., 1960. The child’s conception of geometry.

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. Proc. Natl. Acad. Sci. 101, 5658–5663.

Pitchaimuthu, K., Sourav, S., Bottari, D., Banerjee, S., Shareef, I., Kekunnaya, R., Röder, B., 2019. Color vision in sight recovery individuals. Restor. Neurol. Neurosci. 37, 583–590.

Pizzamiglio, L., Committeri, G., Galati, G., Patria, F., 2000. Psychophysical properties of line bisection and body midline perception in unilateral neglect. Cortex 36, 469–484.

Poirier, C., Collignon, O., DeVolder, A.G., Renier, L., Vanlierde, A., Tranduy, D., Scheiber, C., 2005. Specific activation of the V5 brain area by auditory motion processing: an fMRI study. Cogn. Brain Res. 25, 650–658.

Porquis, L. Ben, Finocchietti, S., Zini, G., Cappagli, G., Gori, M., Baud-Bovy, G., 2017. ABBI: A wearable device for improving spatial cognition in visually-impaired children, in: 2017 IEEE Biomedical Circuits and Systems Conference (BioCAS). IEEE, pp. 1–4.

Port, N.L., Lee, D., Dassonville, P., Georgopoulos, A.P., 1997. Manual interception of moving targets I. Performance and movement initiation. Exp. Brain Res. 116, 406–420.

Postma, A., Zuidhoek, S., Noordzij, M.L., Kappers, A.M.L., 2008. Haptic orientation perception benefits from visual experience: Evidence from early-blind, late-blind, and sighted people. Percept. Psychophys. 70, 1197–1206.

Postma, A., Zuidhoek, S., Noordzij, M.L., Kappers, A.M.L., 2007. Differences between early-blind, late-blind, and blindfolded-sighted people in haptic spatial-configuration learning and resulting memory traces. Perception 36, 1253–1265.

Pouget, A., Ducom, J.-C., Torri, J., Bavelier, D., 2002. Multisensory spatial representations in eye-centered coordinates for reaching. Cognition 83, B1–B11.

Previc, F.H., 1998. The neuropsychology of 3-D space. Psychol. Bull. 124, 123.

Proulx, M.J., Harder, A., 2008. Sensory substitution. Visual-to-auditory sensory substitution devices for the blind. Dutch J. Ergon. voor Ergon. 33, 20–22.

Putzar, L., Hötting, K., Röder, B., 2010. Early visual deprivation affects the development of face recognition and of audio-visual speech perception. Restor. Neurol. Neurosci. 28, 251–257.

Quinn, P.C., 1994. The categorization of above and below spatial relations by young infants. Child Dev. 65, 58–69.

Quinn, P.C., Cummins, M., Kase, J., Martin, E., Weissman, S., 1996. Development of categorical representations for above and below spatial relations in 3-to 7-month-old infants. Dev. Psychol. 32, 942.

Renier, L., De Volder, A.G., 2005. Cognitive and brain mechanisms in sensory substitution of vision: a contribution to the study of human perception. J. Integr. Neurosci. 4, 489–503.

Ricciardi, E., Bonino, D., Pellegrini, S., Pietrini, P., 2014. Mind the blind brain to understand the sighted one! Is there a supramodal cortical functional architecture? Neurosci. Biobehav. Rev. 41, 64–77.

Richardson, M., Thar, J., Alvarez, J., Borchers, J., Ward, J., Hamilton-Fletcher, G., 2019. How much spatial information is lost in the sensory substitution process? Comparing visual, tactile, and auditory approaches. Perception 48, 1079–1103.

Rieser, J.J., Heiman, M.L., 1982. Spatial self-reference systems and shortest-route behavior in toddlers. Child Dev. 524–533.

Rieser, J.J., Rider, E.A., 1991. Young children's spatial orientation with respect to multiple targets when walking without vision. Dev. Psychol. 27, 97.

Rizzolatti, G., Fadiga, L., Fogassi, L., Gallese, V., 1997. The space around us. Science (80-.). 277, 190–191.

Rizzolatti, G., Scandolara, C., Matelli, M., Gentilucci, M., 1981. Afferent properties of periarcuate neurons in macaque monkeys. II. Visual responses. Behav. Brain Res. 2, 147–163.

Rochlis, J.L., 1998. A vibrotactile display for aiding extravehicular activity (EVA) navigation in space.

Rock, I.E., 1997. Indirect perception. The MIT Press.

Röder, B., 2012. Sensory deprivation and the development of multisensory integration. Multisensory Dev. 301–324.

Röder, B., Rösler, F., Spence, C., 2004. Early vision impairs tactile perception in the blind. Curr. Biol. 14, 121–124.

Röder, B., Teder-Salejarvi, W., Sterr, A., Rosler, F., Hillyard, S.A., Neville, H.J., 1999. Improved auditory spatial tuning in blind humans. Nature 400, 162–166.

Rodríguez-Hernández, A.F., Merino, C., Casanova, O., Modrono, C., Torres, M.Á., Montserrat, R., Navarrete, G., BURUNAT, E., GONZÁLEZ-MORA, J.L., 2010. Sensory substitution for visually disabled people: Computer solutions. WSEAS Trans. Biol. Biomed. 7, 1–10.

Rossetti, Y., Gaunet, F., Thinus-Blanc, C., 1996. Early visual experience affects memorization and spatial representation of proprioceptive targets. Neuroreport 7, 1219–1223.

Ruggiero, G., Ruotolo, F., Iachini, T., 2018. Congenital blindness limits allocentric to egocentric switching ability. Exp. Brain Res. 236, 813–820. https://doi.org/10.1007/s00221-018-5176-8

Ruotolo, F., van der Ham, I., Postma, A., Ruggiero, G., Iachini, T., 2015. How coordinate and categorical spatial relations combine with egocentric and allocentric reference frames in a motor task: effects of delay and stimuli characteristics. Behav. Brain Res. 284, 167–178.

Ruotolo, F., Ruggiero, G., Vinciguerra, M., Iachini, T., 2012. Sequential vs simultaneous encoding of spatial information: a comparison between the blind and the sighted. Acta Psychol. (Amst). 139, 382–389.

Sabel, B.A., Strasburger, H., Kasten, E., 1997. Programs for diagnosis and therapy of visual field deficits in vision rehabilitation. Spat. Vis. 10, 499–503.

Salminen, N.H., Tiitinen, H., May, P.J.C., 2012. Auditory spatial processing in the human cortex. Neurosci. 18, 602–612.

Sambo, C.F., Forster, B., 2009. An ERP investigation on visuotactile interactions in peripersonal and extrapersonal space: evidence for the spatial rule. J. Cogn. Neurosci. 21, 1550–1559.

Sampaio, E., Maris, S., Bach-y-Rita, P., 2001. Brain plasticity: “Visual” acuity of blind persons via the tongue. Brain Res. 908, 204–207. https://doi.org/10.1016/S0006-8993(01)02667-1

Sanabria, D., Soto-Faraco, S., Spence, C., 2005. Spatiotemporal interactions between audition and touch depend on hand posture. Exp. Brain Res. 165, 505–514.

Schaffert, N., Janzen, T.B., Mattes, K., Thaut, M.H., 2019. A review on the relationship between sound and movement in sports and rehabilitation. Front. Psychol. 10, 244.

Schenkman, B.N., Nilsson, M.E., 2010. Human echolocation: Blind and sighted persons’ ability to detect sounds recorded in the presence of a reflecting object. Perception 39, 483–501.

Schiatti, L., Cappagli, G., Martolini, C., Maviglia, A., Signorini, S., Gori, M., Crepaldi, M., 2020. A Novel Wearable and Wireless Device to Investigate Perception in Interactive Scenarios, in: 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE, pp. 3252–3255.

Schinazi, V.R., Thrash, T., Chebat, D., 2016. Spatial navigation by congenitally blind individuals. WIREs Cogn. Sci.

Schmidt, S., Tinti, C., Fantino, M., Mammarella, I.C., Cornoldi, C., 2013. Spatial representations in blind people: the role of strategies and mobility skills. Acta Psychol. (Amst). 142, 43—50. https://doi.org/10.1016/j.actpsy.2012.11.010

Schmiedchen, K., Freigang, C., Rübsamen, R., Richter, N., 2013. A comparison of visual and auditory representational momentum in spatial tasks. Attention, Perception, Psychophys. 75, 1507–1519.

Scholz, D.S., Wu, L., Pirzer, J., Schneider, J., Rollnik, J.D., Großbach, M., Altenmüller, E.O., 2014. Sonification as a possible stroke rehabilitation strategy. Front. Neurosci. 8, 332.

Schroeder, C.E., Lindsley, R.W., Specht, C., Marcovici, A., Smiley, J.F., Javitt, D.C., 2001. Somatosensory input to auditory association cortex in the macaque monkey. J. Neurophysiol. 85, 1322–7.

Senna, I., Pfister, S., Martolini, C., Gori, M., Cocchi, E., Ernst, M.O., 2020. Spatial recalibration in cataract-treated individuals. J. Vis. 20, 1011.

Shaffer, D.M., Dolgov, I., Mcmanama, E., Swank, C., Maynor, A.B., Kelly, K., Neuhoff, J.G., 2013. Blind (fold) ed by science: A constant target-heading angle is used in visual and nonvisual pursuit. Psychon. Bull. Rev. 20, 923–934.

Shams, L., Seitz, A.R., 2008. Benefits of multisensory learning. Trends Cogn. Sci. 12, 411–417.

Sherrick, C.E., 1976. The antagonisms of hearing and touch. Hear. Davis Essays Honor. Hallowell Davis 149–158.

Shiell, M., Champoux, F., Zatorre, R., 2016. The right hemisphere planum temporale supports enhanced visual motion detection ability in deaf people: evidence from cortical thickness. Neural Plast.

Shiell, M.M., Champoux, F., Zatorre, R.J., 2014. Enhancement of visual motion detection thresholds in early deaf people. PLoS One 9, e90498.

Shushruth, S., Ichida, J.M., Levitt, J.B., Angelucci, A., 2009. Comparison of spatial summation properties of neurons in macaque V1 and V2. J. Neurophysiol. 102, 2069–2083.

Soto-Faraco, S., Kvasova, D., Biau, E., Ikumi, N., Ruzzoli, M., Morís-Fernández, L., Torralba, M., 2019. Multisensory interactions in the real world. Cambridge University Press.

Soto-Faraco, S., Lyons, J., Gazzaniga, M., Spence, C., Kingstone, A., 2002. The ventriloquist in motion: Illusory capture of dynamic information across sensory modalities. Cogn. brain Res. 14, 139–146.

Soto-Faraco, S., Spence, C., Kingstone, A., 2004. Cross-modal dynamic capture: congruency effects in the perception of motion across sensory modalities. J. Exp. Psychol. Hum. Percept. Perform. 30, 330.

Spagnol, S., Baldan, S., Unnthorsson, R., 2017. Auditory depth map representations with a sensory substitution scheme based on synthetic fluid sounds, in: 2017 IEEE 19th International Workshop on Multimedia Signal Processing, MMSP 2017. Institute of Electrical and Electronics Engineers Inc., pp. 1–6. https://doi.org/10.1109/MMSP.2017.8122220

Spanlang, B., Normand, J.M., Giannopoulos, E., Slater, M., 2010. A first person avatar system with haptic feedback, in: Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST. pp. 47–50. https://doi.org/10.1145/1889863.1889870

Spence, C., Squire, S., 2003. Multisensory integration: maintaining the perception of synchrony. Curr. Biol. 13, R519–R521.

Spencer, C., Spencer, C.J.S., Blades, M., Morsley, K., 1989. The child in the physical environment: The development of spatial knowledge and cognition. John Wiley & Sons Inc.

Squeri, V., Sciutti, A., Gori, M., Masia, L., Sandini, G., Konczak, J., 2012. Two hands, one perception: how bimanual haptic information is combined by the brain. J. Neurophysiol. 107, 544–550.

Starkiewicz, W., Kuliszewski, T., 1963. The 80-channel elektroftalm, in: Proceedings of the Lnternational Congress Technology Blindness, Am. Found. Blindness. p. 157.

Stein, B.E., 2012. The new handbook of multisensory processing. Mit Press.

Stein, Barry E., Meredith, M.A., 1993. The merging of the senses. MIT Press.

Stein, B E, Meredith, M.A., 1993. The Merging of the Senses. Cambridge, MA.: A Bradford Book.

Stevenson, R.A., Fister, J.K., Barnett, Z.P., Nidiffer, A.R., Wallace, M.T., 2012. Interactions between the spatial and temporal stimulus factors that influence multisensory integration in human performance. Exp. Brain Res. 219, 121–137. https://doi.org/10.1007/s00221-012-3072-1

Stoll, C., Palluel-Germain, R., Fristot, V., Pellerin, D., Alleysson, D., Graff, C., 2015. Navigating from a depth image converted into sound. Appl. Bionics Biomech. 2015, 1–9. https://doi.org/10.1155/2015/543492

Strelow, E.R., 1985. What is needed for a theory of mobility: Direct perceptions and cognitive maps—lessons from the blind. Psychol. Rev. 92, 226.

Striem-Amit, E., Amedi, A., 2014. Visual cortex extrastriate body-selective area activation in congenitally blind people “seeing” by using sounds. Curr. Biol. 24, 687–692.

Striem-Amit, E., Cohen, L., Dehaene, S., Amedi, A., 2012a. Reading with sounds: sensory substitution selectively activates the visual word form area in the blind. Neuron 76, 640–652.

Striem-Amit, E., Dakwar, O., Reich, L., Amedi, A., 2012b. The large-scale organization of “visual” streams emerges without visual experience. Cereb. Cortex 22, 1698–1709.

Striem-Amit, E., Guendelman, M., Amedi, A., 2012c. ‘Visual’ acuity of the congenitally blind using visual-to-auditory sensory substitution. PLoS One 7, e33136.

Stronks, H.C., Mitchell, E.B., Nau, A.C., Barnes, N., 2016. Visual task performance in the blind with the BrainPort V100 Vision Aid. Expert Rev. Med. Devices. https://doi.org/10.1080/17434440.2016.1237287

Tabry, V., Zatorre, R.J., Voss, P., 2013. The influence of vision on sound localization abilities in both the horizontal and vertical planes. Front. Psychol. 4, 932.

Thaler, L., Milne, J.L., Arnott, S.R., Kish, D., Goodale, M.A., 2014. Neural correlates of motion processing through echolocation, source hearing, and vision in blind echolocation experts and sighted echolocation novices. J. Neurophysiol. 111, 112–127.

Thinus-Blanc, C., Gaunet, F., 1997. Representation of space in blind persons: vision as a spatial sense? Psychol. Bull. 121, 20.

Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J.-L., Ystad, S., 2014. From sound to shape: Auditory perception of drawing movements. J. Exp. Psychol. Hum. Percept. Perform. 40, 983.

Todd, J.W., 1912. Reaction to multiple stimuli. Science Press.

Tomassini, A., Gori, M., Burr, D., Sandini, G., Morrone, C., 2011. Perceived duration of visual and tactile stimuli depends on perceived speed. Front. Integr. Neurosci. 5, 51.

Trommershauser, J., Kording, K., Landy, M.S., 2011. Sensory cue integration. Oxford University Press.

Ungar, S., Blades, M., Spencer, C., 1995. Mental rotation of a tactile layout by young visually impaired children. Perception 24, 891–900.

Van der Stoep, N., Postma, A., Nijboer, T.C.W., 2017. Multisensory perception and the coding of space.

Vasilyeva, M., Lourenco, S.F., 2012. Development of spatial cognition. Wiley Interdiscip. Rev. Cogn. Sci. 3, 349–362. https://doi.org/10.1002/wcs.1171

Vasilyeva, M., Lourenco, S.F., 2010. Spatial Development, in: The Handbook of Life-Span Development. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470880166.hlsd001020

Vecchi, T., Tinti, C., Cornoldi, C., 2004. Spatial memory and integration processes in congenital blindness. Neuroreport 15, 2787–2790.

Velázquez, R., 2010. Wearable assistive devices for the blind, in: Wearable and Autonomous Biomedical Devices and Systems for Smart Environment. Springer, pp. 331–349.

Vercillo, T., Burr, D., Gori, M., 2016. Early visual deprivation severely compromises the auditory sense of space in congenitally blind children. Dev. Psychol. 52, 847.

Vercillo, T., Gori, M., 2016. Blind individuals represent the auditory space in an egocentric rather than allocentric reference frame. Electron. Imaging 2016, 1–5.

Vercillo, T., Milne, J.L., Gori, M., Goodale, M.A., 2015. Enhanced auditory spatial localization in blind echolocators. Neuropsychologia 67, 35–40. https://doi.org/10.1016/j.neuropsychologia.2014.12.001

Vercillo, T., Tonelli, A., Gori, M., 2018. Early visual deprivation prompts the use of body-centered frames of reference for auditory localization. Cognition 170, 263–269. https://doi.org/10.1016/j.cognition.2017.10.013

Vercillo, T., Tonelli, A., Gori, M., 2017. Intercepting a sound without vision. PLoS One 12. https://doi.org/10.1371/journal.pone.0177407

Verrillo, R.T., Bolanowski, S.J., McGlone, F.P., 1999. Subjective magnitude of tactile roughness. Somatosens. Mot. Res. 16, 352–360.

Verrillo, R.T., Gescheider, G.A., 1975. Enhancement and summation in the perception of two successive vibrotactile stimuli. Percept. Psychophys. 18, 128–136.

Voss, P., 2016. Auditory spatial perception without vision. Front. Psychol. 7, 1960.

Voss, P., Lassonde, M., Gougoux, F., Fortin, M., Guillemot, J.-P., Lepore, F., 2004. Early-and late-onset blind individuals show supra-normal auditory abilities in far-space. Curr. Biol. 14, 1734–1738.

Voss, P., Tabry, V., Zatorre, R.J., 2015. Trade-off in the sound localization abilities of early blind individuals between the horizontal and vertical planes. J. Neurosci. 35, 6051–6056.

Wacker, P., Wacharamanotham, C., Spelmezan, D., Thar, J., Sánchez, D.A., Bohne, R., Borchers, J., 2016. VibroVision: An on-body tactile image guide for the blind, in: Conference on Human Factors in Computing Systems - Proceedings. Association for Computing Machinery, pp. 3788–3791. https://doi.org/10.1145/2851581.2890254

Wandell, B.A., Dumoulin, S.O., Brewer, A.A., 2007. Visual field maps in human cortex. Neuron 56, 366–383.

Wanet, M.C., Veraart, C., 1985. Processing of auditory information by the blind in spatial localization tasks. Percept. Psychophys. 38, 91–96.

Wang, R.F., Simons, D.J., 1999. Active and passive scene recognition across views. Cognition 70, 191–210.

Warren, D.H., 1994. Blindness and children: An individual differences approach. Cambridge University Press.

Warren, D.H., 1977. Blindness and early childhood development. American Foundation for the Blind.

Warren, D.H., Pick, H.L., 1970. Intermodality relations in localization in blind and sighted people. Percept. Psychophys. 8, 430–432.

Warren, D.H., Welch, R.B., McCarthy, T.J., 1981. The role of visual-auditory "compellingness" in the ventriloquism effect: Implications for transitivity among the spatial senses. Percept. Psychophys. 30, 557–564.

Wechsler, D., 2014. WISC-V: Technical and interpretive manual. NCS Pearson, Incorporated.

Wechsler, D., 2012. Wechsler preschool and primary scale of intelligence—fourth edition. Psychol. Corp. San Antonio, TX.

Weeks, R., Horwitz, B., Aziz-Sultan, A., Tian, B., Wessinger, C.M., Cohen, L.G., Hallett, M., Rauschecker, J.P., 2000. A positron emission tomographic study of auditory localization in the congenitally blind. J. Neurosci. 20, 2664–2672.

Wertheimer, M., 1923. Untersuchungen zur Lehre von der Gestalt. II. Psychol. Forsch. 4, 301–350.

Whitney, D., Cavanagh, P., 2000. The position of moving objects. Sci. (New York, NY) 289, 1107.

Withington, D.J., 1992. The effect of binocular lid suture on auditory responses in the guinea-pig superior colliculus. Neurosci. Lett. 136, 153–156.

Wong, M., Gnanakumaran, V., Goldreich, D., 2011. Tactile spatial acuity enhancement in blindness: evidence for experience-dependent mechanisms. J. Neurosci. 31, 7028–7037.

World Health Organization, 1993. The ICD-10 classification of mental and behavioural disorders: diagnostic criteria for research. World Health Organization.

Zahorik, P., 2001. Estimating sound source distance with and without vision. Optom. Vis. Sci. 78, 270–275.

Zampini, M., Shore, D.I., Spence, C., 2003. Audiovisual temporal order judgments. Exp. brain Res. 152, 198–210.

Zwiers, M.P., Van Opstal, A.J., Cruysberg, J.R.M., 2001. A spatial hearing deficit in early-blind humans. J. Neurosci. 21, RC142–RC142.