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Devices for visually impaired people: High technological devices with low user acceptance and no adaptability for children

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ABSTRACT

Considering that cortical plasticity is maximal in the child, why are the majority of technological devices available for visually impaired users meant for adults and not for children? Moreover, despite high technological advancements in recent years, why is there still no full user acceptance of existing sensory substitution devices? The goal of this review is to create a link between neuroscientists and engineers by opening a discussion about the direction that the development of technological devices for visually impaired people is taking. Firstly, we review works on spatial and social skills in children with visual impairments, showing that lack of vision is associated with other sensory and motor delays. Secondly, we present some of the technological solutions developed to date for visually impaired people. Doing this, we highlight the core features of these systems and discuss their limits. We also discuss the possible reasons behind the low adaptability in children.

Contents

1. Introduction

There is a general consensus on the crucial role of visual experience in the development of spatial cognition. Spatial perception is fundamental for numerous human activities, as it provides the ability to internalize and represent the spatial relationships between objects in the environment and one's own body (Hart and Moore, 1973). The condition of blindness provides experimental evidence concerning the role of visual experience in shaping space perception and cognition.

In 2014 the number of visually impaired people worldwide was estimated to be 285 million, of whom 39 million were totally blind and 19 million were children below the age of 15 years (Pascolini and Mariotti, 2011).

It is well known that early onset blindness adversely affects psychomotor, social and emotional development. Consequently, preschool-age children with visual impairments often have difficulties engaging in positive social interactions (Guralnick et al., 1996a,b,c; McConnell and Odom, 1999; Rettig, 1994; Sacks and Kekelis, 1992; Sacks et al., 1992).

The creation of new technological devices to be used early in life is a must. However, despite the huge improvement of technological devices specifically designed for visually impaired users, we find that many of these solutions are not widely accepted by adults and are not easily adaptable to children.

Some of the reasons on why this occurs are that many devices are invasive systems, require too much attention, result in a big

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cognitive load and require long training periods before they can be used (see next paragraphs and Tables 2 and 3).

The aim of this review is to stimulate neuroscientists and technology researchers to carefully consider the contribution that each discipline can provide to the main goal of improving the quality of life of visually impaired individuals.

Firstly, we discuss the development of spatial and social skills in children with visual impairments, showing that lack of vision is associated with many sensory-motor and social disorders. Secondly, we present a list of devices developed for visually impaired people. Doing this, we discuss their limits and show that most of these devices have been developed thinking about only adult capability, without considering their use in children.

2. Visual impairment in children

Compared to audition and touch, vision provides the most precise spatial information about the distal environment. Consequently, individuals with visual impairments might present a delayed or impaired development of spatial capabilities. This is especially true if the visual impairment emerges at birth, when multisensory communication is fundamental for the sensorimotor feedback loop that contributes to the development of spatial representations (Gori, 2015; Gori et al., 2010, 2014; Vercillo et al., 2015b). Since visual feedback represents the most important incentive for actions and thus for the development of locomotion and mobility skills, visually impaired children are also at high risk of presenting motor-related developmental delays or disabilities. Indeed recent studies report that the onset of several motor milestones (e.g. rolling, crawling, standing, balancing etc) is delayed in visually impaired infants (Elisa et al., 2002; Hallemans et al., 2011; Houwen et al., 2009; Levtzion-Korach et al., 2000; Nakamura, 1997), suggesting that the visual feedback of our own body is fundamental for the development of self-concept. Moreover results suggest that blind children do not reach for objects that produce sounds until the end of the first year while sighted children start around 5 months (Bayley, 1993). Similarly, while sighted children start to perform the first individual actions and navigation movements from the age of one year, blind children show the first locomotive skills not before 18–20 months of age, with large individual variability. Some blind children start to walk at 12–13 months of age, as sighted children do, while others at about 30–32 months of age, independently of cognitive and motor development (Perez-Pereira and Conti-Ramsden, 2001; Sampaio et al., 1989). Moreover, it has been shown that totally blind infants presented a clear delay in head control and abnormal, exaggerated type of 'fidgety movements' as well as prolonged period of ataxic features in postural control (Prechtl et al., 2001).

The development of spatial cognition is strictly related to the development of social cognition: the ability to independently navigate and orient ourselves in space facilitates engagement in social interactions. Indeed, a delay in the acquisition of language, motor or cognitive skills can have a direct impact on a child's social competence (Guralnick, 1992; Guralnick et al., 1996b; Rettig, 1994). More recent works highlighted that preschool-age children with visual impairments often have difficulties engaging in positive social interactions, making their assimilation into preschool programs difficult. In fact, many do not display a full range of play behaviors (Guralnick et al., 1996a,b,c; McConnell and Odom, 1999; Rettig, 1994; Sacks and Kekelis, 1992; Sacks et al., 1992) and spend more time engaging in solitary play interacting more with adults than with their sighted peers (Adelson and Fraiberg, 1974; Andersen et al., 1984; Anderson and Kekelis, 1985; Parsons, 1986; Rettig, 1994; Sacks and Kekelis, 1992; Sacks et al., 1992; Schneekloth, 1989; Skellenger and Hill, 1994; Troster et al., 1994; Warren, 1977). Considering that the interaction among peers is essential for the development of cognitive, linguistic, social, and play skills (Hartup, 1979), the aforementioned delay in the acquisition of social competence in visually impaired children gives rise to feelings of frustration, rather than self-efficacy and independence which characterize the social experience of typical children. Indeed, the lack of visual information during early infancy often constitutes a risk for the development of the personality and emotional competence (Troster et al., 1994).

Nonetheless, when assessing social competence in visually impaired people some other factors resulting from the loss of vision should be taken into account. For example, it has been shown that parenting style influences the socio-emotional development of sighted children (Booth, 1994; Harker et al., 2016; Kaufmann et al., 2000; Kochanska et al., 1998; Landry et al., 2001) because parents represent the first influential setting that can produce appreciable differences in developmental outcomes in terms of psychological functioning (Bronfenbrenner and Ceci, 1994; Lomanowska et al. in press).

Inconsistent, hostile and non-sensitive parenting behaviors have been associated with adjustment problems and social adversity in children (Lyons-Ruth et al., 1991; Wakschlag and Hans, 1999) and also with anxiety, depression, and other stress-related illnesses during adolescence (Key, 1995) (Martin et al., 2004) and adulthood (ENNS et al., 2002). We speculate that a similar influence of parenting style holds also for blind children, especially because families of children with visual disabilities are more prone to experience various stressors such as concerns about the social acceptance of the child (Leyser et al., 1996) and to face difficulties in initiating and sustaining social interactions (Moore and McConachie, 1994), thus they might easily develop an over-protective behavior that negatively influences the social development of the visually impaired child. The negative effects of blindness on socio-emotional competence can be observed also in adulthood, with the impoverishment of the ability to perform everyday activities both in private settings like home and in public settings like work place. Importantly, the decrease of functional abilities has been linked to the emergence of serious psychological problems in the blind population (Foxall et al., 1992). Indeed, adults with visual impairments tend to feel more socially isolated and not properly supported compared to sighted individuals (Emerson, 1981; Evans et al., 1982; Fitzgerald, 1970; Fitzgerald et al., 1987; Foxall et al., 1992; Giarratana-Oehler, 1976; Weiner, 1991) and are at higher risk of developing depressive symptoms (Burmedi et al., 2002a,b; Evans et al., 2007; Nyman et al., 2012, 2010; O'Donnell, 2005; Papadopoulos et al., 2014), principally because social competence depends on the ability to utilize visual cues (Van Hasselt, 1983). Overall several scientific findings suggest that visual impairments, especially if acquired later in life, can have profound consequences for the physical functioning, psychological well-being, and health service needs of older adults (Horowitz, 2004).

The difficulties associated with visual impairment in children clearly emerge from these studies and persist in some cases also during adulthood. A summary of some papers assessing spatial perception in visually impaired children and adults are reported in Table 1. Technological solutions could bring significant benefits for the developing children, for example by improving their locomotion, mobility or spatial skills. On the other hand, as we will see in the next paragraphs, many of the technological solutions developed so far have never been tested on children.

3. Sensory substitution devices for visually impaired people

As we have seen in the previous paragraphs, visual impairments not only remove or decrease the intake of information that

Table 1

The table summarizes some of the experimental studies conducted to assess auditory spatial hearing in visually impaired children.

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

The gross motor development of a group of 10 congenitally blind infants has been studied. Results indicate that while the neuromuscular maturation and postural achievements were on average compared to sighted controls, both self-initiated mobility and locomotion were delayed, suggesting that this delay might be associated with the normally late adaptive substitution of sound for sight as incentive for mobility.

Ashmead et al. (1998). Spatial hearing in children with visual disabilities. Perception 27, 105–122

The spatial cognition of 35 visually impaired children (aged 6-20 years old) has been evaluated with a comprehensive assessment of spatial-hearing ability, including psychophysical estimates of spatial resolution in the horizontal, vertical, and distance dimensions, as well as measures of reaching and walking to the locations of sound sources. The spatial hearing of the children with visual disabilities was comparable to or somewhat better than that of the sighted children and adults, implying that the developmental calibration of human spatial hearing is not dependent on a history of visual experience.

Bigelow, A.E. (1986). The development of reaching in blind children. British Journal of Developmental Psychology, 4, 355–366

The development of object awareness has been studied in 5 congenitally blind infants (11–32 months) with tasks designed to investigate the sequential development of reaching and search and highlight the relative importance of sound and touch in eliciting a reaching movement. Results indicate that object awareness, initially guided by touch rather than sound, has the same developmental trend in both sighted and visually impaired children.

Bigelow, A.E. (1992). Locomotion and search behavior in blind infants. Infant Behavior and Development 15, 179–189

The relationship between locomotion and object search was longitudinally studied in 3 blind infants by examining the timing between the emergence of crawling and walking and the infants' performance on reaching tasks indicative of advancement in object permanence. Despite developmental delays in both abilities, the emergence of locomotor skills was related to the development of object permanence, demonstrating that the absence of vision determines spatial impairments and the relationship between object search and locomotion is facilitative.

Cappagli, G. et al. (2015). Auditory and proprioceptive spatial impairments in blind children and adults. Developmental Science. doi: 10.1111/desc.12374

Auditory distance discrimination and proprioceptive reproduction with the dominant arm have been measured in 17 visually impaired participants (n = 10 children from 9 to 17 years of age, n = 7 adults from 20 to 72 years of age). Compared to sighted controls (n = 68), congenitally blind subjects presented a substantial spatial impairment for both tasks, while late blind adults do not show any spatial impairments. The results suggest that vision is important for the development of space cognition and the acquisition of a visual frame of reference early in life is allows to develop some specific non-visual spatial skills.

Cappagli, G. and Gori, M. (2016). Auditory spatial localization: Developmental delay in children with visual impairments, Research in Developmental Disabilities, 2016, 53–54, 391

Auditory spatial localization has been compared between a group of 69 sighted individuals (57 children with mean age of 10.5 years old and 12 adults with mean age of 35years old) and a group of 31visually impaired individuals (10 totally blind children with mean age of 12.3 years old, 10 low vision children with mean age of 11.6 years old, 7 early blind adults with mean age of 32 years old and 4 late blind adults with mean age of 37 years old). The task consisted of pointing with the cane held in the dominant hand towards the sound produced in turn by 11 out of 23 loudspeakers positioned horizontally in a straight line. Contrary to what expected from literature review, children with visual impairments show a significant developmental delay in the acquisition of auditory spatial localization if compared with age matched sighted controls, suggesting that the effects of the absence of vision on the representation of auditory space might be compensated through the development.

Cornoldi, C. et al. (1998). Individual differences in the capacity limitations of visuospatial short-term memory: Research on sighted and totally congenitally blind people. Memory & cognition 19, 459–468 (1991)

Visuospatial imagery capacity was explored in 20 congenitally blind subjects (aged 15–60 years old) by asking people to follow an imaginary pathway through either two- or three-dimensional matrices of different complexity. Compared to sighted controls (n = 20), blind subjects show capacity limitations with three-dimensional patterns, revealing that the blind's deficit involves both visual and spatial configurations. A plausible explanation for these limits is that only visual experience may create the ability of simultaneously managing a high number of items.

Elisa, F. et al. (2002). Gross motor development and reach on sound as critical tools for the development of the blind child. Brain and Development 24, 269–275

The early neuromotor development has been studied in 20 congenitally blind or severely visually impaired children, nine without (B) and 11 with associated handicaps (B + H), with the mean age at first observation at 11.4 months (range: 4–30 months) and the mean follow-up duration at 16.9 months (range: 3–36 months). The assessment included developmental history, neurological examination, video-recording of spontaneous activity and administration of the Reynell-Zinkin Scales and neuroradiological and neurophysiological investigations. Overall they found that all the B + H subjects except one displayed absence of almost all neuromotor functions and just one (9%) of the B + H children developed satisfactory fine motor abilities, suggesting that early intervention to improve postural-motor development in these subjects is fundamental.

Fazzi, E. et al. (2011). Reach on sound: A key to object permanence in visually impaired children. Early human development 87, 289–296

The cognitive development in congenitally blind children with or without multiple disabilities has been assessed with a cohort study by enrolling 37 congenitally blind subjects (17 with associated multiple disabilities, 20 mainly blind) and using the Bigelow's protocol to evaluate "reach on sound" capacity over time (at 6, 12, 18, 24, and 36 months) while clinical features have been assessed via a battery of clinical, neurophysiological and cognitive instruments. Results indicate that while mainly blind subjects manifested the ability to reach an object presented through sound, most of the blind children with multiple disabilities presented a poorer performance, indicating that the presence of extra disabilities might interact with the assessment of cognitive functioning in blindness.

Gori, M. et al. (2010). Poor haptic orientation discrimination in non-sighted children may reflect disruption of cross-sensory calibration. Current Biology 20, 223–5

Size and orientation haptic discrimination thresholds have been measured in 17 congenitally visually impaired children (aged 5-19 years old). Haptic orientation thresholds were greatly impaired compared with age-matched controls, whereas haptic size thresholds were equal or better. The results provide strong support for cross-modal calibration hypothesis, which states that during development vision calibrates other senses for spatial competences.

Hallemans, A. et al. (2011). Development of independent locomotion in children with a severe visual impairment. Research in developmental disabilities 32, 2069–2074

Locomotion skills have been evaluated in children and adults with a visual impairment (ages 1–44, n = 28) compared to that of age-related individuals with normal vision (n = 60) by asking participants to walk barefoot at preferred speed while their gait was recorded by a Vicon system while several locomotion parameters were assessed (e.g. walking speed). Adaptive strategies have been found in the group with visual impairment, such as a slower walking speed, a shorter stride length, a prolonged duration of stance and of double support.

Houwen, S. et al. (2009). Physical activity and motor skills in children with and without visual impairments. Medicine and science in sports and exercise 41, 103–109

The physical activity level of children with and without visual impairments has been assessed by the GT1 M accelerometer and motor skill performance by the Test of Gross Motor Development-2 in 96 children with and without visual impairment aged between 6 and 12 years old. Total activity, time spent in sedentary activities and participation in moderate-to-vigorous physical activity were significantly lower in children with visual impairment, with total activity and participation in moderate-to-vigorous physical activity being positively correlated with object control scores and time spent in sedentary activity inversely correlated with locomotor and object control scores. The results emphasize the importance of promoting an active lifestyle in children.

Levtzion-Korach, O. et al. (2000). Early motor development of blind children. Journal of paediatrics and child health 36, 226–229

The motor developmental pattern of 40 blind children has been evaluated compared to the data assessing 10 motor skills of typical sighted children and to the motor developmental milestones of the Bayley Developmental Scale and the Revised Denver Developmental Screening Test. The motor development of blind children was delayed, the delay being significant in all 10 motor skills that were examined. This delay emphasizes the major importance of vision as a sensory input modality for the process of sensory– motor development.

Table 1 (*Continued*)

Leyser, Y. et al. (1996). Stress and adaptation in families of children with visual disabilities. Families in Society: The Journal of Contemporary Social Services 77, 240–249

Stress level and coping strategies have been assessed in a sample of 130 families of visually impaired children and compared to a control group of 78 families of sighted children by analyzing the responses to a parent questionnaire and the Family Environment Scale (FES). Results showed that families of visually impaired children experienced more stressors such as concerns about the social acceptance of the child, and used personal coping strategies as well as various formal and informal sources of support.

Moore, V., and McConachie, H. (1994). Communication between blind and severely visually impaired children and their parents. British journal of developmental psychology *12*, 491–502

The communication style adopted by parents towards children has been analyzed in eight families of totally blind children and eight families of children whose vision was severely impaired. All children were visited at home at around 18 months of age and were video-recorded while interacting with a familiar caretaker. Several differences in terms of communication style have been highlighted in both groups, such a tendency for the parents of blind children to initiate interactions themselves, use verbal comments unaccompanied by actions, avoid talking about objects which were at the child's current focus of attention and request verbal information from their children.

Parsons, S. (1986). Function of play in low vision children: II. Emerging patterns of behavior. Journal of Visual Impairment & Blindness 80 (6), 777–784

Patterns of play behavior in a structured free-play situation with toys have been analyzed via 15-minutes videorecording sessions in 18 low vision and 18 sighted children aged between 20 months and 4 years 6 months. The play behaviors were coded into 4 categories of play: functional, stereotypical, relational, and undifferentiated. The presence of visual impairment was associated with significantly less functional and more stereotypical play behavior, indicating quantitative and qualitative differences between groups.

Prechtl, H.F. et al. (2001). Role of vision on early motor development: lessons from the blind. Developmental Medicine & Child Neurology *43*, 198–201

The motor development of 14 visually impaired infants with no evidence of brain damage has been evaluated with the examination of video recordings of the first year of like (n = 13) and/or the preterm period (n = 6) and compared to normative data form previous studies carried out by the authors. Results indicate that around 2 months postterm all infants showed clear delay in head control and abnormal, exaggerated type of 'fidgety movements' and postural control was characterized by a prolonged period of ataxic features, suggesting that from the first months onwards blindness does indeed affect early motor development.

Schneekloth, L.H. (1989). Play environments for visually impaired children. Journal of Visual Impairment & Blindness 83(4), 196–201

The motor skills and environmental interactions among peers have been assessed in a group of of 36 blind, partially sighted and sighted children with mean ages of 5.1, 5.7, and 8.5 years respectively with the –administration of selected non sight-dependent items from the Bruininks-Oseretsky Test of Motor Proficiency. The results of the analysis highlight some motor interactions with the environment. motor developmental delays in visually impaired children that could be explained in terms of lack of gross motor interactions with the environment.

Skellenger, A.C., and Hill, E.W. (1994). Effects of a shared teacher-child play intervention on the play skills of three young children who are blind. Journal of Visual Impairment & Blindness 88(5):433–445

The effects of baseline versus intervention strategies to increase the amount and type of targeted play behavior have been assessed for 5 months via videorecordings for 3 visually impaired children aged between 5 and 7 years old, with intervention strategy consisting in a shared teacher–child play program. Overall the play behavior of all 3 children improved with implementation of the intervention, indicating the effectiveness of shared teacher–child play as a method of increasing the play skills of young children with visual impairments.

Troster, H. et al. (1994). Longitudinal study of gross-motor development in blind infants and preschoolers 1. Early Child Development and Care 104, 61–78

The gross-motor development of 10 congenitally blind children has been longitudinally assessed during the first 3 years of life and compared to developmental norms for sighted children. Both groups of preterm and full-term blind children differed from sighted children in the acquisition of motor skills required for self-initiated changes in posture and position (sitting or standing) and in crawling, suggesting that blindness-specific and blindness-nonspecific causal factors exist when considering the gross-motor development.

Vercillo, T et al. (2016) Early visual deprivation severely compromises the auditory sense of space in congenitally blind children Developmental Psychology;52(6):847–53

The audio performance of 8 blind and 52 sighted children was evaluated by performing two spatial tasks (minimum audible angle and space bisection) and one temporal task (temporal bisection). Results indicate that there was no impairment in the temporal task for blind children but, like adults, they showed severely compromised audio thresholds for spatial bisection. Interestingly, the blind children also showed lower precision in judging minimum audible angle.

vision normally provides but they also cause some spatial and social deficits at the cognitive level. This analysis suggests that technology must address two different types of problems: the first is to substitute the absent sensory information with another signals, and the second is to rehabilitate the impaired cognitive ability. This latter aspect is particularly evident when the visual impairment occurs early in life, during the period when these abilities normally develop.

Most of the technology developed to date has followed the first approach, which aims at substituting the visual information with another modality. In particular, Sensory Substitution Devices (SSDs), convert the stimuli, normally accessed through one sensory modality, into stimuli accessible to another sensory modality. Specifically, sensory substitution devices for visually impaired individuals aim at supplying the missing visual information with visual-to-tactile or visual-to-auditory conversion systems (Proulx and Harder, 2008) (Table 2 reports a list of SSDs developed to date and their main features and field of application).

In most of the substitution systems based on visual-to-tactile conversion, images captured by a camera are converted into tactile stimulations and transmitted to users. In the mid '60s, Bach-y-Rita created the Tactile-Visual Sensory Substitution device (TVSS) that converts signals from a video camera into tactile stimulation applied to the back of the subject (Bach-y-Rita et al., 1969a). Moving the camera, visually impaired subjects lying on the grid were able to recognize lines and shapes (Bach-y-Rita et al., 1969a). Bach-y-Rita's studies can be considered the initiator of the development of sensory substitution systems based on human-machine interfaces. Technological progress then allowed the development of much smaller, portable devices, such as head-mounted devices, wrist-bands, vests, belts, shoes etc., which allow hands-free interactions (Velázquez, 2010). To date several SSDs based on small electro-tactile and vibro-tactile stimulators placed on various body surfaces (e.g. fingers, wrist, head, abdomen, feet (e.g. Bach-y-Rita et al., 1998; Kaczmarek and Bach-Y-Rita, 1995; Kajimoto et al., 2003)) have been developed (see Table 2). Contrarily to the visual-to-tactile sensory substitution device, in systems based on visual-to-auditory conversion, the images captured by a camera are converted into sounds and transmitted to users via headphones. One of the best known visual-to-auditory devices is the vOICe developed by Meijer (Meijer, 1992b). It associates height with pitch and brightness with loudness in a left-to-right scan of the visual image. Many other visual-to-auditory sensory devices have been developed to date and are reported in Table 2.

These can be grouped into three broad categories according to the type of information that the device transmits.

Vision substitute. The first category regroups SSDs that aim at converting images or videos directly into tactile or audio sig-

Table 2
Table that summarize all sensory substitution devices and their features.

SSD: Tactile			
Name	*Information Transmitted*	*How it works*	*Task*
Tactile Visual Sensory Substitution Device (TVSS) (Bach-Y-Rita et al., 1969b; Bach-y-Rita and Kercel, 2003)	Image	The video data are transmitted to a tongue display unit that converts the video into a pattern of 144 low-voltage pulse trains each corresponding to a pixel. This stimulates the touch sensors on the dorsum of the subject's tongue.	To convert the image from a video camera into a tactile image.
Tongue Display Unit (TDU) (Kaczmarek, 2011; Kaczmarek and Bach-Y-Rita, 1995)	Image	It creates real-time tactile images on the tongue, thanks a tactile display 12 × 12 translating visual information given by a computer. It is a portable battery-powered device.	To perform research to determine the best electrode geometry and intensity control method.
Finger- Braille interface (Hirose and Amemiya, 2003; Matsuda et al., 2007; Matsuda et al., 2008)	Language	These interfaces have mechanical fingers, which they use to transmit Braille symbols. They use a code where each finger is associated with a dot of the Braille code. A wearable version for navigation purpose has been developed.	To allow communication with and between deaf-blind persons. The wearable version is used in navigation applications to guide and obtain environmental information.
Kahru Tactile Outdoor Navigation (Jones et al., 2006)	Directions	It is a wearable tactile harness-vest display for directional navigation instructions thanks to a set of six vibrating motors. All communicate through a belt-worn infrared receiver.	To convert navigation information into tactile inputs.
NavBelt (Shoval et al., 1998)	Image or directions	It is a belt connected to a computer and ultrasonic sensors that provides acoustic feedback in two modes or operations: guidance mode, where the direction or the target location is known to the system and an acoustic or tactile signal actively guides the user; image mode, where an acoustic or tactile image of the environment is presented to the user	To translate images or maps of the environment into acoustic or tactile information to allow a safe and quick walk
Sonicguide (Kay, 2000, 2001)	Sounds	It has ultrasonic transmitter and two microphones. It has also a rechargeable battery which allows for 4–5 h of continues use. The transmitter is directional and emits ultrasonic sound, modulated four times per second, in a beam which is about 90°. The Sonic Guide produces sound in two independent channels, one for the left and one for the right. The individual using the device binaurally thus has the advantage of comparing signals reaching the two ears.	To translate echoes in sounds for navigating and scanning objects.
Sonic Eye (Sohl-Dickstein et al., 2015)	Sounds	It uses speakers, mounted on a helmet, to produce ultrasonic "chirps" based on bat echolocation calls. After the reflection produced by the chirps they are recorded by two microphones, placed at the sides of the helmet in artificial pinnae modeled after a bat ear. These recordings are played back to the user stretched to be heard by the human ear	To amplify echoes produced by ultrasonic sounds in order to locate objects in space
iGlasses (Rempel, 2012)	Navigation	They have ultrasonic sensor located on the frame. As output, they emit a pulsing vibration that change in frequency in relation of the distance and size of the surface of an object.	Translate ultrasound information in tactile outputs
Shoe-integrated tactile display (Velãzquez et al., 2009)	Directions	Uses an array of 16 vibrotactile actuators located in the middle part of the foot sole. The motor that the actuator is made of is capable of vibrating within a range of 10–55 Hz	To test direction recognition, shape identification, pattern recognition and navigation in space thanks to vibrotactile stimulation of the sole of the foot
Brainport Vision (Arnoldussen and Fletcher, 2012; Lee et al., 2014; Nau et al., 2015)	Image	To translate visual info into tactile information thanks to a camera that captures visual data. The information is converted into a spatially encoded signal via an electrode array. Each pixel differentiates the data as differences in pulse characteristics such as frequency, amplitude and duration. The array should be located on the tongue	To perceive and identify objects
Refreshable braille display (Yobas et al., 2003)	Language, text	Electro-mechanical device for displaying braille characters, in general connected to computer	To make computer content (document, web) accessible by replacing the monitor
Optacon (Arezzo and Schaumburg, 1980; Hislop et al., 1983; Van Boven et al., 2000; Weisgerber, 1973)	Text (image)	A 24 × 6 inch metal rod matrix allows the development of a tactile image of the printed letters.	To read printed material that has not been transcribed into Braille
SSD: Audio			
The Voice (Auvray et al., 2007a; Meijer, 1992a)	Image	The image is converted into a sound pattern via a special computer connected to a standard television camera. It uses an approximate inverse spectrographic mapping. The complex sound obtained represents images up to a resolution of 64 × 64 pixels with 16 gray-tones per pixel.	To see pictures and images.

Table 2 (*Continued*)

SSD: Tactile

Name	*Information Transmitted*	*How it works*	*Task*
Prosthesis for Substitution of Vision by Audition (PSVA) (Capelle et al., 1998)	Image	The image is converted into a sound pattern. It uses a standard camera and a direct non-scanning mapping. The maximum resolution is 124 pixels.	To see pictures and images.
K-sonar http://www.ksonar.com	Sounds	It produces ultrasonic waves. The echoes reflected by the objects are translated by the K sonar receiver into unique invariant tone-complex sounds that the user could listen thanks to miniature headphones.	To translate echoes in sounds for navigating and scanning objects.
SmartSight (Cronly-Dillon et al., 1999; Cronly-Dillon et al., 2000)	Image	A personal computer is programmed to simulate a keyboard which is used to generate the sound patterns associated with different high-contrast line contours of visual shapes.	To convert line contours of visual shapes into audio patterns.
Vibe (Auvray et al., 2005)	Image	The Vibe device converts a video stream into a stereophonic sound stream. It requires a webcam and a computer. It uses a kind of virtual retina that has two levels of 'cells': sensors and receptors. Each sensor corresponds to a particular pixel, while a receptor is a set of neighboring sensors. Each receptor produces a signal that can be interpreted as a sound. The signals of all the receptors are mixed together to produce a stereo audio output.	To convert a video stream into an audio stream in real time.
EyeMusic (Abboud et al., 2014)	Image	Similar to PSVA. A specific algorithm conveys shape, location and color information using sound.	To provide visual information through a musical auditory experience.
Text-to-Speech Systems (Allen et al., 1987; Moulines and Charpentier, 1990; Sproat, 1997)	Language	Systems combining a video camera, optical character recognition (OCR) and speech synthesis software.	To read written documents
KNFB Reader (LCC, 2016)	Image, text, language.	An App that makes a photo and reads documents on the go.	To read written documents.
Prizmo 3 (S.P.R.L., 2015)	Image, text	Prizmo 3 is a scanning application with Optical Character Recognition (OCR) in over 40 languages with powerful editing capability, text-to-speech.	To scan and read documents.
Voice Over and Talking Tap Twice (TTT) (Apple; Central, 2014)	Language, text	Screen read built into a smartphone. It treats the user interface as a hierarchy of elements, which are navigated by various keystrokes	To make the smartphone accessible to visually impaired people.

Table 3

Table that summarizes devices for visually impaired people and their use in users.

Name	Tested in users	Everyday life use	Adaptability in children: if tested and used, distinction between preschool (<5 years old) and school children
Tactile Visual Sensory Substitution Device (TVSS)	Sighted and blind adults	No, not commercialized	Needs extensive training to be used. Never tested on children.
Tongue Display Unit (TDU)	Sighted and blind adults	No, not commercialized	Needs extensive training to be used. Never tested on children.
Finger- Braille interface	Blind adults	No, not commercialized	Never tested on children.
Kahru Tactile Outdoor Navigation	Adults	No, not commercialized	Never tested on children.
NavBelt	Adults	No, not commercialized.	Never tested on children.
Sonicguide	Blind adults	Commercialized as K-sonar	Never tested on children.
Sonic Eye	Adults	No, not commercialized.	Never tested on children.
iGlasses		Yes, commercialized.	Tested on deaf children.
Shoe-integrated tactile display	Sighted and blind adults	No, not commercialized.	Never tested on children.
Brainport Vision	Sighted and blind adults	Yes, commercialized.	Never tested on children.
Optacon	Blind adults and children	Yes it was commercialized in the '70s.	It has been used by adults and high school children. Not tested on preschool children.
The Voice	Sighted and Blind adults.	Yes, via a smartphone app.	Not tested on children.
Prosthesis for Substitution of Vision by Audition (PSVA)	Sighted and blind adults.	No, not commercialized	Not tested on children.
K-sonar	Blind adults	Yes, commercialized.	It could be used in children but never tested yet
SmartSight	Blind adults.	No, not commercialized.	Not tested on children.
Vibe	Blind adults.	No, not commercialized.	Not tested on children.
MusicEye	Blind adults.	Yes, via a smartphone app.	Not tested on children.
KNFB Reader	Blind people.	Yes, it is an app for Android and iOs.	There is no record about it. The app can be downloaded by everyone.
Prizmo 3	Sighted and blind people.	Yes, it is an app for Android and iOs.	There is no record about it. The app can be downloaded by everyone.
Voice Over and Talking Tap Twice (TTT)	Blind adults and children.	Yes, they are built into smartphone's services.	Tested and used by school children.

nals. Studies with these devices have shown that users can use visual-to-tactile substitution systems in tasks that would normally require vision, like localization tasks (Jansson, 1983) and simple form recognition (Kaczmarek and Haase, 2003; Sampaio et al., 2001). Similarly, it has been shown that visual-to-auditory sensory substitution devices are potentially useful for object localization (Auvray et al., 2007b; Renier et al., 2005), form recognition (Arno et al., 1999, 2001; Cronly-Dillon et al., 1999, 2000; Pollok et al., 2005) and spatial tasks (Cronly-Dillon et al., 2000). However, the factual observation that none of these devices are actually used by visually-impaired persons show that the proposed technology presents serious limits. Clearly, none of these devices has succeeded in conveying the information usually obtained by the visual system. Converting all pixel values of high-resolution images into equivalent tactile or audio signals does not appear feasible. The spatial resolution of the tactile modality varies from 1 mm at the fingertips to several centimeters on the dorsum. Representing a 640 × 480 VGA image would require a fingertip surface almost as large as the whole dorsum (that is about 64 by 48 cm). Transmitting an image via the audio modality raises the problem of transforming rich spatial information into a time signal, which requires either some form of image scanning or a complex code. In either case, the amount of information that can be effectively be transmitted is much lower than what vision normally provides.

Navigation aids. Vision plays such an important role for orienting oneself and navigating. A lot of effort has been put into developing navigation aids for visually-impaired persons. Many different devices have been proposed, some of them are sonar based. These devices, before to convert the output information into sound (or touch), use ultrasound information to sense the surroundings and acquire spatial information (e.g. NavBelt (Shoval et al., 1998), K-sonar, http://www.ksonar.com/), Sonic Eye (Sohl-Dickstein et al., 2015), SonicGuide (Kay, 2000, 2001), iGlasses (Rempel, 2012), while others are mere guidance devices that provide directional cues (e.g. Kahru Tactile Outdoor Navigator (Jones et al., 2006)). It is somewhat surprising that few of these devices have been adopted. To a large extent, the cane and the dog are still the auxiliaries that are most used by visually-impaired persons.

Reading aids. The third category of devices aims at transmitting written information, which might be printed or in electronic form. These devices might convert the printed or electronic text into Braille or directly into speech. Nowadays, Refreshable Braille displays are clearly less popular than text-to-speech programs. One important reason for this situation is the decrease of Braille literacy among the blind. In the 1950s, about half of blind children learned to read Braille, according to the National Federation of the Blind. Today, that figure is just 10 percent (Abboud et al., 2014). Refreshable Braille displays are still expensive devices and learning Braille requires extensive training. In contrast, text-to-speech programs make it easier and faster to consume electronic information. For example, both iOs VoiceOver (Apple), Android TalkBack (Central, 2014) and many other apps make smartphone content accessible to the visually impaired population and are widely used. Other program have made considerable progress in recognizing letters in scanned or filmed text since the beginning of this technology in the 70 s (Kleiner, 1977). For example, apps such as KNFB Reader (LCC, 2016) or Prizmo (S.P.R.L., 2015) can nowadays transform a smartphone into a reliable reading machine. Despite the popularity of the text-to-speech system, it should nevertheless be noted that the main American association for the blind negatively considers the disaffection for Braille. Braille provides a privileged form of access to written material and literacy that is formative and also correlates in some forms with employment (e.g. see Ryles, 1996 for a more detailed frame).

In Table 3 we have reported some indications of the level of user studies carried out with the SSDs considered in Table 2. As can be seen, many of these systems have been tested only in experimental conditions and are not used in everyday life by visually impaired people. Only few of them have been commercialized and used by children.

4. Low user acceptance in children and adults

If we focus on SSDs and navigation aids, it is possible to make some remarks on why they might not be widely adopted. In particular SSDs result even more difficult to use with children than with adults.

Invasive system: a first issue could be that most of these devices are invasive. For example, most of them cover the ears (e.g. The Voice), block the tongue (e.g. the Tongue Display Unit, TDU) and involve the use of the hands (e.g. the Brainport Vision). This is problematic if we consider for example that visually impaired people prefer to be free to listen to auditory information from the environment and to have their hands free. Furthermore, these devices are usually physically heavy to transport and not easily adaptable, in terms of size and weight, they are not easily used by children. For example the original TVSS was a standalone system, comprising a chair, and a control box (see (White et al., 1970a,b)).

Cognitive load: a second issue could be that processing acoustical or tactile signals might overwhelm the cognitive abilities of the user. Less dramatically, using these devices might simply require too much attention, which makes it difficult for the user to focus on the main task. In addition, the audio or tactile feedback, that is produced as output, is usually quite complex to interpret. To interpret the new sensory input, users need to memorize the transformation rules employed by the computer to convert the sensory signals and to undergo extensive training, which requires high attentional capabilities. Taking as example The Voice, the information about the contrast between light and dark in a visual image is conveyed with sounds of different frequencies.

Training: a third issue could be that many of these devices require a long period of training in order to be used. To interpret the new sensory input, users need to memorize the transformation rules employed by the computer to convert the sensory signals, and to undergo extensive training. This is worse in children that have limited attentive skills compared to adults.

Poor performance: a fourth issue could be that the level of performance of these systems is insufficient to justify the invasiveness and effort needed to use them.

No action perception link: another aspect to consider is that many of the SSDs described above do not take into account the important link established by action and perception in the learning process. Experimental results suggest that there is no perception without action (Lenay et al., 2003) and experimental data suggest that the users' movement is crucial to learn how to properly explore the environment with a sensory substitution device. For example Bach-y-Rita's TVSS only works if the subject can actively manipulate the camera (Bach-y-Rita, 1972; White et al., 1970a,b).

Lack of multisensory integration: another important aspect that could influence mainly the usability of SSDs in children is that many of these devices provide a large amount of acoustical and tactile signals that have to be integrated in a multisensory way. It is known that children before 10 years of age do not show some forms of multisensory integration [e.g. (Gori, 2015; Gori et al., 2008a,b, 2012a; Gori and Hanganu-Opatz, 2015; Gori et al., 2012b, 2010, 2014, 2011, 2012c; Vercillo et al., 2015a)]

Not clinically validated: A more general problem related to technological development today, not only that present in this field, is that most of these devices remain prototypes without arriving to everyday life use of users. Indeed, only few devices have been extensively tested on users. Those that have arrived to the point of experimental evaluation involved only few subjects in the study. If we consider for example the robotic exoskeleton domain, we can observe the same phenomenon. Jarrassé et al. (2014) reviewed the robotic exoskeleton platforms, showing that many of these systems are not tested on patients and those that are tested are at a pre-clinical level. This is a big issue if we consider that to be helpful for users the devices have to be validated on a large sample of patients through standardized clinical trials.

4.1. Technology for children

To our knowledge, only a preliminary study has considered the possibility of adapting a visual-to-tactile sensory substitution device developed for blind adults to visually impaired infants (Segond et al., 2007). The attraction power of the tactile stimulation produced by the device has been preliminarily assessed in sighted infants, showing that infants actively searched for the tactile stimulation and pursued the stimulation when it was contingent to their self-movement. Thus, the artificial tactile stimulation produced by the sensory substitution device could apparently motivate the exploratory behavior and the interaction activities of sighted infants. However, there are no clues to understand whether the same rule also applies to blind infants.

Another aspect that is completely neglected in the development of devices for both children and adults is related to the improvement of social skills. As we have seen in the previous paragraph, lack of vision has a significant impact on the social interaction skills of blind children with peers. So far, to our knowledge the only platform that provides access to essential visual information during social encounters has been developed for visually impaired adults (Krishna et al., 2008). The audio signal generated from the face detection helps the user to know when someone approaches, allows them to choose whether to initiate a conversation, and helps to determine when to make eye contact.

Starting from the limits of the existing technology for children discussed above, and from our neuroscientific results (e.g. Gori et al., 2014), we have recently developed a new rehabilitative technology for blind and low vision children called ABBI, the Audio Bracelet for Blind Interaction. Recent studies suggest that the communication between sensory modalities is fundamental for a correct unisensory and multisensory development. For example, the visual information seems to be fundamental for the development of spatial perception in the haptic modality (Gori, 2015; Gori et al., 2008b, 2010, 2014, 2011; Vercillo et al., 2015b) and inaccurate visual signals can provide clear effects on the development of correct spatial information in the auditory system (Knudsen and Knudsen, 1985). Another recent insight is that the development of spatial capabilities is also driven by the reciprocal influence between visual perception and execution of movements (Brambring, 2006). Children use visual information to construct a sense of space by associating visual and motor related signals. The success of an action is monitored by matching the expected change of sensory, mostly visual information with the observed changes and these sensori-motor feedback loops are principally important in early infancy and childhood. Starting from these results, the idea behind ABBI is that it is possible to rehabilitate the spatial and social deficits by exploiting a natural audio-motor association. When moving the arm, a sighted children can observe their own actions and their consequences. In the absence of vision, visual feedback of the movement is not available. ABBI produces an audio signal (positioned in the main effectors) that provides spatial sensory feedback similar to that used by sighted children. Indeed, the audio movement will convey spatial information, allowing a representation of the movement in space to be built in an intuitive and direct manner. ABBI can also be used by people other than the visually impaired person, such as therapists or parents, in order to map the extra-personal space around him. We have now tested the ABBI system with low vision and congenitally blind children, performing 3 months longitudinal studies. Preliminary data suggest an improvement of spatial skills after the use of the device in the audio, haptic and motor domain in children from 6 to 18 years of age (Finocchietti et al., 2015b).

5. Discussion

This review poses an important question about the direction that Sensory Substitution Devices are taking. Indeed, although in the past decade we have observed many technological advancements in the development of devices for visually impaired people, we are still far from seeing systems used in everyday life by users, especially children.

We tried to identify some reasons why there is no user acceptance of existing sensory substitution devices and why the majority of technological devices available for visually impaired users are meant for adults and not for children. As we have seen, lack of visual experience is also associated with several social difficulties that might negatively influence the quality of life of the visually impaired individuals. For these reasons early intervention is a must. We highlighted some difficulties related to the use of these devices in adults and in children, for example the necessity of learning a new language, of following long training programs and of integrating multiple sensory signals. We also proposed a new rehabilitative solution (ABBI) that can be used in children with visual impairments to improve spatial skills from the first years of life. More generally, we think that every technological development should start from the neuroscientific understanding of the brain mechanism that subtends the deficit. For example, we have demonstrated that in the absence of vision, some haptic and audio skills are impaired in visually impaired children and adults (Cappagli et al., 2015; Finocchietti et al., 2015a; Gori et al., 2010). Thus, merely converting a visual into an audio signal, as some new devices actually do, might be not sufficient to globally improve the sense of space in visually impaired people. The information that is conveyed has to be associated with the user capability on assimilating that information. For example, by understanding which brain mechanisms globally determine the difficulty in perceiving space, it is possible to develop more effective solutions tailored to the problem. We hope that this review will open a new discussion among neuroscientists and engineers, providing some input to help develop technological devices more accepted by users and adaptable to children with visual impairments.

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