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The Causal Role of Vision in the Development of Spatial Coordinates: Evidence From Visually Impaired Children

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Many findings suggest that visual deprivation in early life negatively affects the development of spatial competence and that sighted and visually impaired individuals use different strategies to encode spatial positions. This study aims to assess the role of vision in developing spatial coordinates by running three studies in a sample of children and adolescents with and without visual impairments ($n = 42$, 16 female, 8–18 years old, 100% European), using visual and auditory versions of Simon task with uncrossed and crossed hands posture. The first study assessed that visual and auditory external coordinates mature in parallel in sighted children. The second showed that if vision is available but degraded, it is sufficient to calibrate spatial performance in the auditory system, even if the visual performance remains impaired. The third experiment showed that the total lack of visual experience results in an impaired spatial performance also in the other spared modalities. Our results suggest that vision impairments have different consequences on developing spatial competence. They also highlighted the necessity of early assessment and interventions in visually impaired children that take into account different residual abilities.

Public Significance Statement
The results suggest a causal role of visual experience in the development of spatial abilities. Moreover, these findings evidence the necessity of different training for low-vision and blind children, as they show different abilities in the no-deprived sensory modalities.

Keywords: spatial reference frame, spatial cognition development, Simon effect, blindness, visual impairments

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Spatial cognition is the set of abilities that allows individuals to navigate and interact with the environment, and it plays an essential role in everyday life. In the spatial cognition domain, all sensory information is combined in spatial representations based on the spatial reference frames (Vasilyeva & Lourenco, 2012). The spatial reference frame relies upon two main coordinate systems: the anatomical or internal and the external coordinates, which indicate the coordinates used to code the location of stimuli, respectively, dependent or independent of body posture.

Internal and External Reference Frames

The internal frame considers skin-based coordinates that are integrated with information about current body posture and are updated when body posture changes while limbs move. In contrast, the external frame employs spatial coordinates that can still be eye-, head-, or trunk-centered, independent from body posture (Badde & Heed, 2016; Burgess, 2008; Klatzky, 1998). In recent years, there has been growing interest in identifying the developmental steps necessary to acquire

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The studies involving human participants were reviewed and approved by the local competing ethical committee (Comitato Etico, ASL3 Genovese; Prot. IIT_UVIP_COMP_2019 N. 02/2020, July 4, 2020). The participants or their guardians provided their written, informed consent to participate in this study.

The data supporting the conclusions of this article will be made available by the authors at https://zenodo.org/communities/myspace/?page=1&size=20.

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complete spatial competence from an early age. Several studies advocate for a gradual development of the ability to incorporate information about body posture with sensory processing in the first year of life (Begum Ali et al., 2015; Bremner et al., 2008; Rigato et al., 2014; Thomas et al., 2017) that continues into early childhood (Begum Ali et al., 2014; Pagel et al., 2009). The dramatic changes in limbs, body, and head shapes and sizes during childhood may partially explain this gradual development (Lampl et al., 1992). Nevertheless, the ability to integrate the sensory information with external and internal frames into a coherent spatial strategy considering the body posture appears around the age of 5–6 years (Bullens et al., 2010; Nardini et al., 2006; Pagel et al., 2009) and seems to be fully matured around the age of 8–9 years (Bollini et al., 2021; Martolini et al., 2020; Pagel et al., 2009).

The Role of Vision in the Development of Spatial Reference Frame

There is a general consensus in the academic field on the crucial role of vision in guiding the maturation of spatial cognition (Cappagli & Gori, 2020; Pasqualotto & Newell, 2007). Vision allows the simultaneous perception of multiple objects in a unique configuration, enabling the understanding of object-to-object relationships (Merabet & Pascual-Leone, 2010; Pasqualotto, Finucane, & Newell, 2013; Thinus-Blanc & Gaunet, 1997). Moreover, studies on sighted individuals suggest that the visual modality provides the most accurate and reliable information about spatial properties. Indeed, it has been demonstrated that during a perceptual conflict, sighted individuals rely less on audition and touch in the case of the simultaneous presence of visuospatial information (Alais & Burr, 2004; Anderson & Zahorik, 2011; Botvinick & Cohen, 1998; Kramer et al., 2020; Pick et al., 1969). Regarding children, instead, recent studies showed how vision is overly used by them and affects their spatial performance as they use visual information more than adults when performing different types of spatial tasks (Petrini et al., 2015, 2016). In addition to evidence in sighted individuals, one of the most striking demonstrations of the central role of vision in the development of spatial competence is the presence of spatial impairments in people without visual input during their early life. Early sensory deprivation can negatively impact the acquisition of adult-like abilities. Specifically, the performance of early-blind adults appears to decrease during spatial tasks that require the use of the external frame, while they show similar behavior to sighted controls when the performance depends upon internal coordinates (Cattaneo et al., 2008; Gori et al., 2014; Iachini et al., 2014; Pasqualotto, Spiller, et al., 2013; Vercillo et al., 2018). Furthermore, these findings are also confirmed by animal studies demonstrating that during auditory-spatial learning tasks, visual feedback is necessary for the creation of acoustic spatial representation (Heffner & Heffner, 1992; King et al., 1988; King & Moore, 1991; Knudsen, 1988; Knudsen et al., 1991).

Visual Deprivation and Spatial Competence

The above findings suggest that visual deprivation in early life negatively affects spatial competence in adults and that sighted and visually impaired adults use different strategies to encode spatial positions (Martolini et al., 2020; Thinus-Blanc & Gaunet, 1997; Vercillo et al., 2016). However, very little is known about the development of external coordinates in visually impaired children. Understanding if and how visual impairment affects the development of children's spatial abilities would be crucial to increasing knowledge of the causal role of vision in acquiring spatial competence. The results from scientific research on auditory-spatial skills in children with visual impairments are contrasting. For instance, it has been found that visually impaired children show outstanding performance in sound localization (Ashmead et al., 1998). Conversely, other studies have demonstrated how visual disabilities cause a developmental delay with impaired performance in auditory-spatial tasks (e.g., spatial bisection, minimum audible angle, and audio depth tasks; Cappagli, Cocchi, & Gori, 2017; Cappagli & Gori, 2016; Fazzi et al., 2011; Fraiberg, 1977; Vercillo et al., 2016). Moreover, to date, it is unclear whether the complete absence or the partial loss of vision would affect the development of the external reference frame.

The Development of Spatial Reference Frame Across Sensory Modalities

Recent research has shown the role of vision in calibrating the external frame during childhood, but it remains unclear if the maturity of the spatial reference frame is acquired with the same developmental steps in all the sensorial modalities (for a recent review, see Cappagli & Gori, 2019). The literature about the typical development of the spatial reference frame in early life has mainly focused on spatial tasks involving visual and proprioception (Garcia et al., 2015; Petrini et al., 2016). Nevertheless, spatial actions in daily life involve multisensory inputs processed to create a spatial representation of the environment. Such representation primarily involves visual, auditory, and tactile inputs in various uni- or multimodal combinations (Holmes & Spence, 2004). To the best of our knowledge, few studies have directly compared the development of spatial competence in visual and touch modalities (Begum Ali et al., 2014; Bremner et al., 2008; Martolini et al., 2021), and there are no studies on the auditory modality.

In the present study, we focused on the development of external frames in typically developed and visually impaired children. Specifically, we assessed if auditory and visual external coordinates mature with the same developmental steps in typically developed children (Experiment 1). Then, we evaluated whether partial (Experiment 2) or complete (Experiment 3) loss of vision determines a delay in developing spatial competence. We used acoustic and visual versions of Simon's task to test our hypotheses. The Simon task (Simon & Wolf, 1963) is a stimulus-response compatibility (SRC) paradigm. It involves implicit spatial processing considering that the spatial information is entirely irrelevant to perform the task. Since the spatial processing is implicit, we could investigate which reference frame was automatically triggered. Moreover, we asked children to perform the task with their hands crossed over the body's midline. The crossed hands posture generates a conflict between spatial coordinates because the left hand is located in the right space and vice versa. This conflict made it possible to explore the implicit interaction between external and internal frames. According to the cross-sensory calibration theory (Gori et al., 2012), given the high reliance on vision during spatial tasks, especially in children, we would expect that auditory information is calibrated to some extent by the visual modality. So we hypothesized that in Experiment 1, there would be no difference between auditory and visual modality as the availability of visual input would calibrate the system. Instead, we would expect there would be no calibration of the auditory information when vision is completely missing, thus impacting performance (in Experiment 3). In contrast, if vision is degraded but still present (Experiment 2), some sort of calibration would happen, allowing the development of external coordinates in the auditory modality.

Method

Participants

Forty-two children and adolescents took part in the study. Twenty sighted participants were recruited from local contacts between 2021 and 2022 ($M_{age} = 11.75$, $SD = 2.69$; 7 female). Twenty-two congenital visually impaired children were recruited from a local rehabilitation center (David Chiossone Institute, Genoa, Italy) based on their visual acuity (VA), measured with the LogMAR scale (Logarithm [log10] of the Minimum Angle of Resolution; Bailey & Lovie, 1976). Twelve of them were legally blind, that is, LogMAR ≥ 1.3 ($M_{age} = 11.98$, $SD = 3.21$; 6 female), and 10 had a low vision ($M_{age} = 11.87$, $SD = 2.22$; 3 female). We recruited children according to the "International Statistical Classification of Diseases and Related Health Problems, 10th Revision" (ICD-10; World Health Organization, 1993; see Table 1 for clinical details). The rehabilitators assessed all the visually impaired children's cognitive level by checking that all children reached an adequate level of cognitive development appropriate for their participation in the study. The sighted children were also used as a control group and with a similar age range and gender distribution of visually impaired children. The local ethics committee approved the study, and all participants' parents (or their legal representatives) signed written informed consent forms under the Declaration of Helsinki.

A priori power analysis was conducted to determine the minimal sample size using a simulation-based approach using *mixedpower* (Kumle et al., 2021) package in R (R Development Core Team, 2011). This approach has been proven efficient in determining the sample size needed in linear mixed-model analysis with interactions between groups and a within-subject condition. The analysis was run on a simulated dataset based on Röder et al.'s (2007) results that used the same task in blind adult participants. We explored the power for a simulated sample size of 10, 15, 20, 25, 30, and 40 participants, running 1,000 simulations with an alpha error probability of 0.05. Power reached 88% with a sample size of 15 for the effect of interaction between hands' posture and group in our simulated dataset. This ensured that our samples of 12 blind and 10 low-vision participants yielded high power. We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study, and we follow *Journal Article Reporting Standards* (Kazak, 2018). The authors will make the data supporting this article's conclusions available on the Zenodo repository (https://zenodo.org/communities/myspace/?page=1&size=20). This study's design and its analysis were not preregistered.

Apparatus and Stimuli

Auditory Task

Two speakers were placed 50 cm from the participants for the audio stimuli and separated by 100 cm (Figure 1A). The warning tone was a sine-wave tone lasting 250 ms (1,000 Hz 97.3 dB), presented simultaneously through both speakers. The target sounds were two natural animal sounds (stimulus 1: rooster sound 80.8 dB; stimulus 2: hen sound Hz 78.9 dB) and could be presented either in the right or left speaker; the speakers were at $\pm 90°$ from the participants' body midline.

Table 1

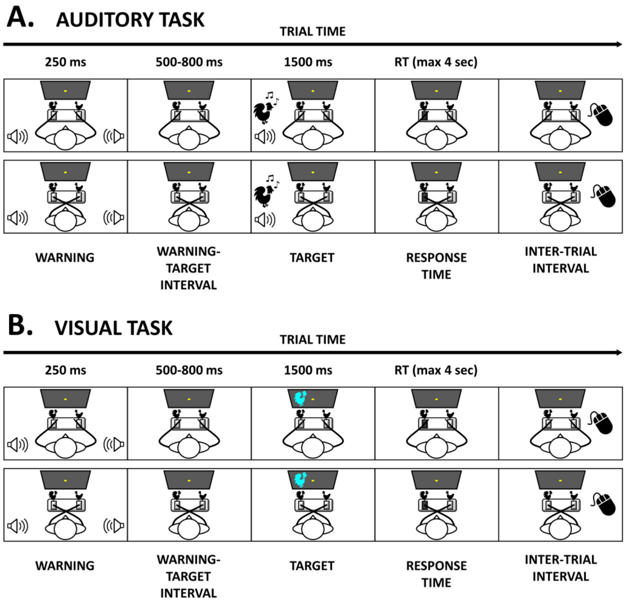
The Table Shows the Sex, Age at the Test, the Group Subdivision, Pathology, and VA Expressed in the LogMAR Scale at a Distance of 3 m of Visually Impaired Participants

Participant #	Sex	Age	Group	Pathology	VA (LogMAR)
1	M	11.23	Blind	Coloboma	1.3
2	M	9.83	Blind	Glaucoma and corneal opacity	1.3
3	F	15.96	Blind	Retinopathy of prematurity	No light perception
4	M	8.69	Blind	Retinopathy of prematurity	No light perception
5	M	10.63	Blind	Bilateral anophthalmia	No light perception
6	M	11.86	Blind	Glaucoma	No light perception
7	F	10.63	Blind	Right anophthalmia and left microphthalmia	1.3
8	F	9.33	Blind	Retinopathy of prematurity	No light perception
9	M	8.73	Blind	Glaucoma	1.3
10	F	17.64	Blind	Retinopathy of prematurity	No light perception
11	F	18.13	Blind	Retinopathy of prematurity	No light perception
12	F	11.06	Blind	Leber congenital amaurosis	1.3
13	F	12.52	Low vision	Retinopathy of prematurity	0.7
14	M	9.37	Low vision	Albinism and nystagmus	1.00
15	M	10.34	Low vision	Familial exudative vitreoretinopathy	0.30
16	M	13.29	Low vision	Albinism and nystagmus	1.00
18	M	11.14	Low vision	Retinopathy of prematurity and glaucoma	1.00
19	M	11.08	Low vision	Nystagmus	0.40
20	M	13.76	Low vision	Nystagmus	0.70
21	M	8.69	Low vision	Microphthalmia	0.30
22	F	10.57	Low vision	Foveal hypoplasia	0.70
23	F	16.57	Low vision	Retinopathy of prematurity	1.0

Note. VA = visual acuity; LogMAR = Logarithm (log10) of the Minimum Angle of Resolution; M = male; F = female.

Figure 1

Schematic Representation of the Experimental Procedure for the Auditory Simon Task (A) and the Visual Simon Task (B)



Note. For each task, the top panel represents an example of a congruent trial with uncrossed hands' posture, while the bottom panel represents a congruent trial with crossed hands' posture. Hen and chicken icons are from Vecteezy (Vecteezy.com). See the online article for the color version of this figure.

Visual Task

The visual stimuli were presented on a 22-in. LCD with a refresh rate of 60 Hz (resolution 1920 × 1080, viewing distance of 57 cm; Figure 1B). The warning tone was the same for the auditory task. The visual target stimuli were cyan or fuchsia silhouette pictures of animals with a size of 10° (stimulus 1: rooster picture; stimulus 2: hen picture) appearing against a black background. They could be presented either on the right or left side of the yellow fixation point (2°) in the center of the screen with an eccentricity of 10°. This size and color were chosen to have high contrast that is distinguishable by children with severe visual impairment. Moreover, the hen and rooster were presented in one unique color throughout the experiment. We made this choice so that children with very severe visual impairment could discriminate between the two stimuli aided by the color feature, resulting in Simon's classic visual paradigm. To the best of our knowledge, no influence of no-opponent colors on reaction time has been reported (McKeefry et al., 2003).

Procedure

The experiment was run using Psychtoolbox-3 (Kleiner et al., 2007) on Matlab® 2018b. The children were comfortably seated at a table with their hands on a computer keyboard in front of the screen. Each trial began with the acoustic warning, followed by a random delay between 500 and 800 ms. We chose an auditory warning for both visual and auditory tasks so that children with very severe visual impairment could have a clear warning of the arrival of the stimulus, as opposed to the classic flicker or color change of fixation that was likely to be missed. After the delay, the target appeared on the left or right side. The children were instructed to respond as fast as possible, discriminating if the stimulus was a hen or a rooster, pressing the left or right button on a pc keyboard (i.e., "q" and "p" keys), irrespective of stimulus location. The stimulus/response-key assignment was counterbalanced across participants; in this way, half of the participants had to press q for the rooster and p for the hen, and the other half had the opposite instruction. After 4 s from stimuli onset, the trial was considered null if the participant did not respond. The subsequent trial started with a mouse click by the experimenter after a random delay (see Figure 1). In each task, each child performed two blocks of 54 trials, one block with uncrossed hands' posture and one block with crossed hands. The order of sensory modality tested was pseudorandomized and balanced among participants. Children with blindness performed just the auditory task.

Data Analysis and Statistics

In order to statistically compare the audio and visual stimuli (which produce really different reaction times [RTs]), we calculated the Simon effect (i.e., the congruency effect). We defined the Simon effect based on the association between stimulus position and keyboard key position (left/right): a trial was congruent if the stimulus and the key had the same position (left/right) regardless of the hands' posture (crossed/uncrossed). The first 10 trials of each condition were excluded from the final analysis and used as a training session. For each participant, we removed responses that were three median absolute deviations (MADs) above or below the median as a robust way to remove outliers (Leys et al., 2013). In addition, due to technical issues, we had to remove additional trials from three participants at the beginning or at the end of one task (from 15 to 19 trials, for Participants *# 4, 13, 20*). Then, we employed a similar procedure adapted from our precedent work (Bollini et al., 2021) by calculating an integrated speed and accuracy score to avoid a conflict between accuracy and speed scores, that is, the linear integrated speed–accuracy score (LISAS; Vandierendonck, 2017). Indeed, in tasks where subjects are trained to respond as quickly as possible without losing accuracy, it is challenging to interpret participants' strategies, especially in children, where the strategies have been demonstrated to change across the ages (Rival et al., 2003). LISAS has proven to detect effects in either RTs or accuracy and to show a stronger sensitivity than other integrated indices (Bollini et al., 2020; Vandierendonck, 2018). LISAS is defined as

$$\text{LISAS} = \text{RT}_{\text{cond}} + \text{PE}_{\text{cond}} \times \frac{\sigma \text{RT}_{\text{tot}}}{\sigma \text{PE}_{\text{tot}}} \tag{1}$$

where RT_{cond} is the subject's average RTs in a specific condition, PE_{cond} is the participant's proportion of errors (PE) in that same condition, $\sigma\text{RT}_{\text{tot}}$ is the participant's overall RT standard deviation in every condition, and $\sigma\text{P}_{\text{Etot}}$ is the participant's overall proportions of errors standard deviation, in every condition. In this way, the errors are weighted with the RT and PE standard deviations ratio to achieve a similar weight for the two measures, RT and PE (Vandierendonck, 2018). Higher scores on LISAS indicate worse performance (i.e., slower and less accurate) and vice versa. We calculated the Δ-Simon effect (incongruent–congruent LISAS scores) for each condition to compare the auditory and visual performances.

For the analysis of the outcomes of Simon tasks, maximum linear mixed-effects models (LMM) with the Kenward–Roger (KR) procedure were used. To this end, we used the *lme4* package (Bates et al., 2007). We chose this type of analysis because it allows the possibility of controlling the variances associated with random factors, like random effects for participants in behavioral scores, and it is more robust against unbalanced size/variance of samples and missing data compared to traditional analyses of variance (Kuznetsova et al., 2017). The effect size (semipartial R^2, $R_p{}^2$) of LMM was calculated using the KR approach using package *r2glmm* (Jaeger et al., 2017). Then, we performed the post hoc tests on the levels of the significant interactions estimated using *emmeans* package (Lenth et al., 2020) with Bonferroni's correction in the contrast of interest (i.e., uncrossed vs. crossed hands posture). Here, to test our hypothesis, we conducted three different experiments.

Experiment 1

In this experiment, we evaluated if the external spatial reference frame is developing with the same timing steps in typically developed children in auditory and visual modalities. We compared the Δ-Simon effects with an uncrossed and crossed hands posture in visual and acoustic Simon tasks as a function of the age. The fixed effects of the model were the within-subjects factor "Hand Posture" (uncrossed and crossed), the within-subjects factor "Sense" (visual and auditory), and all the respective interactions. Moreover, we used participants' ages as a covariate to test whether age influences the dependent variables or not. The variability of the within-subjects effects was taken into account by modeling them as random intercepts nested within the participant factor. The model formula is

$$\Delta - \text{Simon LISAS} \sim \text{Hand Posture} \times \text{Sense} + \text{age} + (1\ \text{participant}) + (1\ \text{Hand Posture:participant}) + (1|\text{Sense:participant}) \quad (2)$$

Experiment 2

In this second experiment, we evaluated if partial visual loss affects the development of the external spatial reference frame by comparing the performance of visually impaired children with typically developed children. We compared the Δ-Simon effects with an uncrossed and crossed hands posture in visual and acoustic Simon tasks as a function of the age. The fixed effects of the model were the between-subjects factor "Group" (low-vision and sighted children), the within-subjects factor "Hand Posture" (uncrossed and crossed), the within-subjects factor "Sense" (visual and auditory), and all the respective interactions. The variability of the within-subjects effects was taken into account by modeling them as random intercepts nested within the participant factor. The model formula is

$$\Delta - \text{Simon LISAS} \sim \text{Group} \times \text{Hand Posture} \times \text{Sense} + \text{age} + (1\ \text{participant}) + (1\ \text{Hand Posture:participant}) + (1\ \text{Sense:participant}) \quad (3)$$

Experiment 3

In this third experiment, we evaluated if the total absence of visual inputs during early age impacts on the development of the auditory external spatial reference frame. Here, we compared the performance in the auditory task of blind and sighted children in acoustic Simon tasks as a function of the age. The fixed effects of the model were: the between-subjects factor "Group" (blind and sighted children); the within-subjects factor "Hand Posture" (uncrossed and crossed), and the respective interactions. Age was used as a covariate, and participants as random factors. The model formula is

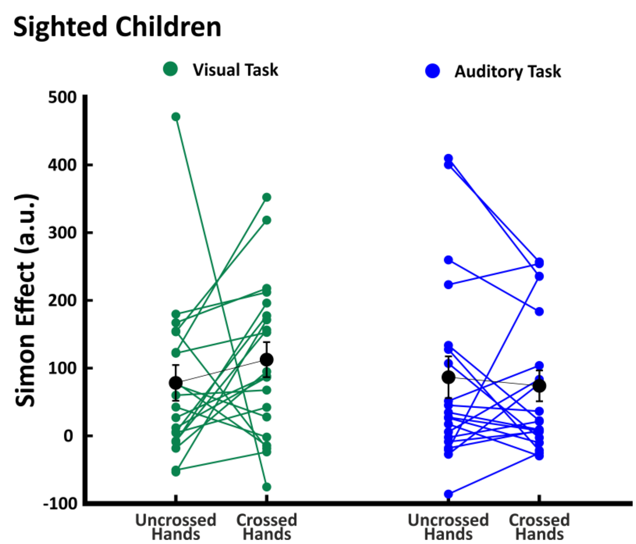
$$\Delta - \text{Simon LISAS} \sim \text{Group} \times \text{Hand Posture} + \text{age} + (1|\text{participant}) \quad (4)$$

Results

Experiment 1

To compare the development of sighted children's spatial abilities in visual and auditory modalities, we contrasted the Δ-Simon effects between an uncrossed and crossed hands posture in auditory and visual Simon tasks. The results are shown in Figure 2. The model outcome revealed no effect on *Sense*, $F(1, 19) = 0.37$, $p = .55$, $R_p{}^2 = 0.01$, or *Hands Posture*, $F(1, 19) = 0.19$, $p = .01$, $R_p{}^2 = 0.62$, and no interaction between them, $F(1, 19) = 1.47$, $p = .24$, $R_p{}^2 = 0.08$. Yet, we found a significant effect for the covariate age, $F(1, 18) = 10.26$, $p < .005$, $R_p{}^2 = 0.26$. This outcome showed no differences when children adopted a crossed posture, showing a full development of the external spatial frame. Moreover, there

Figure 2
Results of Experiment 1 for the Visual Simon Task (Left) and the Auditory Simon Task (Right)



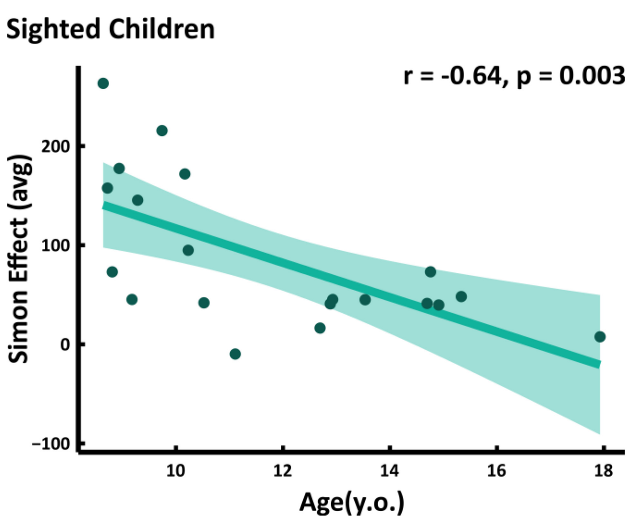
Note. The results report each child's performance in each condition, expressed as the difference between incongruent and congruent LISAS scores. The black dots represent the group average with the relative SEM bars. LISAS = linear integrated speed–accuracy score, SEM = Standard error of the mean. See the online article for the color version of this figure.

was no difference between the visual and auditory tasks, suggesting that sighted children might develop with the same steps. Age had an influence on the Simon effect. Indeed, we found a negative correlation between the average of Δ-Simon effect LISAS and age ($r = -.64$, $p = .003$), see Figure 3, meaning that younger children showed a greater Simon effect (see Figure S1 in the online supplemental materials for a representation of children's performance as a function of age). Finally, we used one-sample t tests against zero, with Bonferroni's correction, to test the presence of the Simon effect. All the one paired t tests revealed the presence of the Simon effect in all modalities and conditions: auditory uncrossed hands: $t(19) = 2.76$, $p_{\text{bonf}} = .02$, Cohen's $d = 0.62$; auditory crossed hands: $t(19) = 3.18$, $p_{\text{bonf}} = .01$, Cohen's $d = 0.71$; visual uncrossed hands: $t(19) = 2.91$, $p_{\text{bonf}} = .02$, Cohen's $d = 0.65$; visual crossed hands: $t(19) = 4.30$, $p_{\text{bonf}} < .001$, Cohen's $d = 0.96$.

From Figure 2, three participants stand out as having a very different pattern to most of the others, particularly one participant in the visual task and two in the auditory task. Indeed, we tested for outliers, and we found that these three children showed scores that were more than three scaled MADs from the median. When we rerun the analysis excluding these three outliers, we obtained a similar outcome, that is, only the covariate age had a statistically significant effect. In any case, we decided to keep the outlier children because this effect was expected with our wide range of age (8–18 years old). For this reason, we corrected our model using the covariate age to check its influence on our data. Bollini et al. (2021) found that children younger than 10 years old showed an incomplete development of the external spatial frame and the absence of the Simon effect with crossed hands posture. Indeed, the outlier children were among the youngest (i.e., 8.6, 8.9, and 9.2 years old). Please refer to Figure S1 in the online supplemental materials to see single child's performances as a function of age, with darker dots for younger children and lighter dots for older children.

Figure 3

Results of Correlation Analyses of Experiment 1



Note. The dots represent single child performance as a function of age. Green shading represents 95% confidence intervals. See the online article for the color version of this figure.

Experiment 2

Here, we assessed whether a partial visual loss would affect the Δ-Simon effects in auditory or visual modalities. The results are shown in Figure 4. The model's outcome revealed a meaningful interaction between the *Group*, *Sense*, and *Hand Posture*, $F(1, 28) = 6.13$, $p = .019$, $R_p^2 = 0.18$. No other effects were reported (all p values $> .16$). Particularly, we did not find any effect of the age, $F(1, 27) = 1.36$, $p = .256$, $R_p^2 = 0.05$. The post hoc contrasts showed that there was a difference between sighted and low-vision children and between uncrossed and crossed hands posture conditions in the visual task, $t(50) = 2.50$, $p_{\text{bonf}} = .03$, Cohen's $d = 1.38$; while in all the other conditions, there were no differences between uncrossed and crossed posture or groups (all p values $> .66$). For a representation of low-vision children's performance as a function of age, see Figure S2 in the online supplemental materials.

Experiment 3

Lastly, we assessed if the absence of vision from the early months of life would impact the development of the external frame. The results are shown in Figure 5. The model's outcome revealed a main effect of the *Hand Posture*, $F(1, 30) = 5.59$, $p = .024$, $R_p^2 = 0.24$; and interaction between *Hand Posture* and *Group*, $F(1, 30) = 9.24$, $p = .004$, $R_p^2 = 0.23$. Moreover, we did not find an effect of the age, $F(1, 29) = 2.13$, $p = .155$, $R_p^2 = 0.07$. The post hoc contrasts showed a difference between uncrossed and crossed hands posture conditions only in the blind group, $t(30) = 3.85$, $p_{\text{bonf}} \leq .001$, Cohen's $d = 1.57$.

Furthermore, we also compared the auditory task performance between blind and low-vision children. This analysis was in line with the previous model outcome. Indeed, we found a main effect of the *Hand Posture*, $F(1, 20) = 5.16$, $p = .024$, $R_p^2 = 0.18$, and interaction between *Hand Posture* and *Group*, $F(1, 20) = 4.35$, $p = .049$, $R_p^2 = 0.18$. The post hoc contrasts revealed a difference between uncrossed and crossed hands posture conditions only in the blind group, $t(20) = 3.08$, $p_{\text{bonf}} = .011$, Cohen's $d = 1.26$ (see Figure 6). For a representation of blind children's performance as a function of age, see Figure S3 in the online supplemental materials.

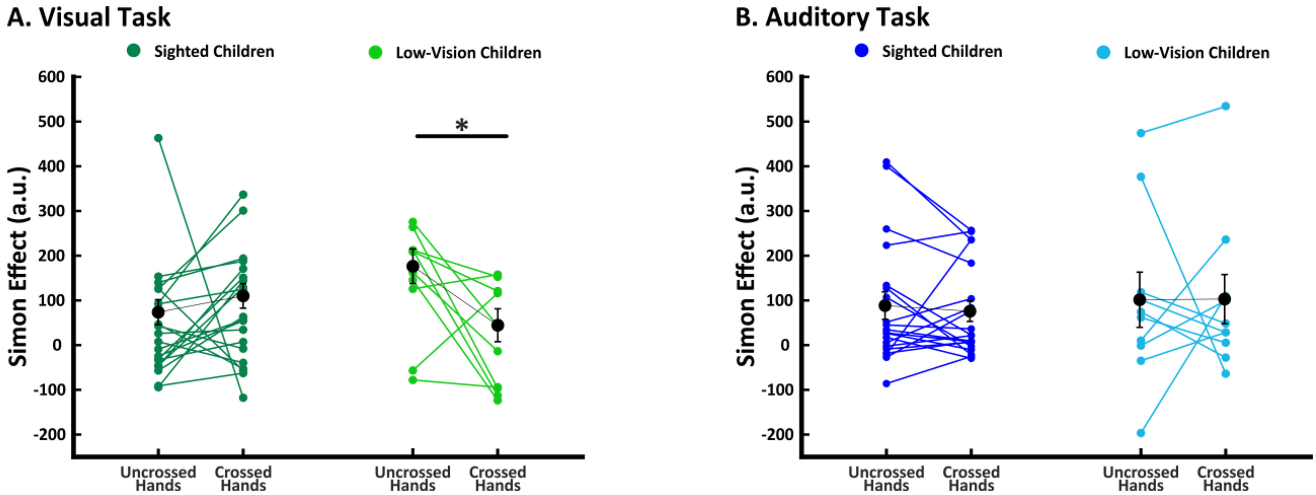
We must highlight that in Experiment 3, in the blind children group, there is the presence of outlier data (see Figures 5 and 6). We repeated our analysis, excluding the two main outlier subjects (Participants 7 and 9, Table 1). As a result, both the interaction between Hand Posture and Group, $F(1, 28) = 6.67$, $p = .015$, $R_p^2 = 0.11$, and the post hoc contrast, $t(28) = 3.17$, $p_{\text{bonf}} < .01$, Cohen's $d = 1.42$, survived, demonstrating that the difference between uncrossed and crossed posture was a general blind group trend and not drove by outlier data. We decided to include these two blind children because we cannot exclude that those apparent outliers are simply due to the natural variability generally observed in impaired subjects. Moreover, their outlier behavior might reflect a relationship between brain reorganization and individual variability. Indeed it has been demonstrated that brain plasticity manifests variably across blind individuals (Sen et al., 2022).

Discussion

This study aimed to investigate the role of vision in the developmental course of spatial frames of reference. Specifically, we tested

Figure 4

Results of Experiment 2 for the Visual Simon Task (A) and the Auditory Simon Task (B)



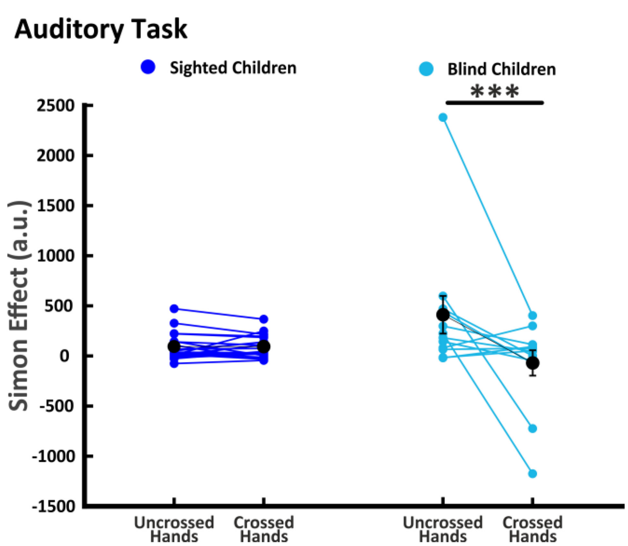
Note. The results report each child's performance in each condition, expressed as the difference between incongruent and congruent LISAS scores. The black dots represent the group average with the relative SEM bars. The darker left columns represent the performance of sighted children, while the lighter right columns represent low-vision children's performance. LISAS = linear integrated speed–accuracy score, SEM = Standard error of the mean. See the online article for the color version of this figure.

* $p_{\text{bonf}} < .05$.

three hypotheses: (a) if auditory and visual external coordinates mature with the same developmental steps in typically developed children; (b) if partial loss of vision determines a delay in developing spatial competence in the same way in auditory and visual modalities; and (c) if the absence of visual experience affects the development of external reference frame. We tested typically developing and

Figure 5

Results of Experiment 3 for the Auditory Simon Task in Blind and Sighted Children

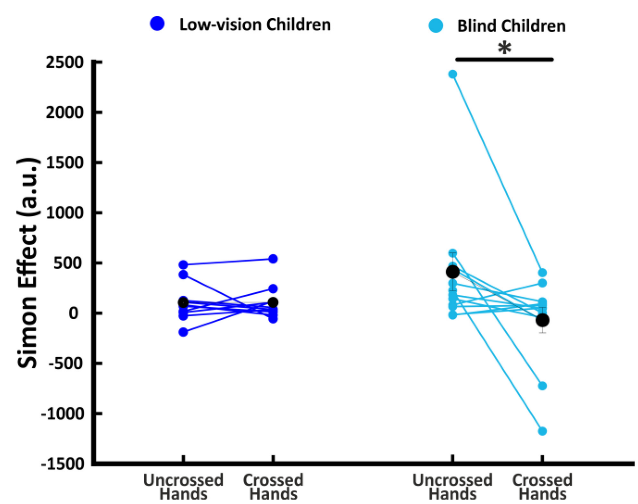


Note. The results report each child's performance in each condition, expressed as the difference between incongruent and congruent LISAS scores. The black dots represent the group average with the relative SEM bars. The left darker column represents the performance of sighted children, while the right lighter column represents blind children's performance. LISAS = linear integrated speed–accuracy score, SEM = Standard error of the mean. See the online article for the color version of this figure.

*** $p_{\text{bonf}} < .001$.

Figure 6

Results of Experiment 3 for the Auditory Simon Task in Blind and Low-Vision Children



Note. The results report each child's performance in each condition, expressed as the difference between incongruent and congruent LISAS scores. The black dots represent the group average with the relative SEM bars. The left darker column represents the performance of low-vision children, while the right lighter column represents blind children's performance. LISAS = linear integrated speed–accuracy score, SEM = Standard error of the mean. See the online article for the color version of this figure.

* $p_{\text{bonf}} < .05$.

visually impaired children in visual and auditory versions of the Simon task. Two different conditions were employed: one with uncrossed hands parallel and the other with hands crossed over the body midline. This manipulation created a conflict between the external and internal coordinates and allowed us to determine the full maturation of the external spatial frame.

In Experiment 1, we did not find any differences between the Simon effect with uncrossed and crossed hands between auditory and visual tasks. We found a main effect of age, indicating a progression in the development of spatial ability in sighted children. These results are in line with our previous findings, where we demonstrated that in children younger than 7 years old, the crossed hands posture affected the Simon effect, whereas, at 10 years of age, children performed as adults and were not affected by such conflict (Bollini et al., 2021). Those findings referred only to the auditory modality, but with Experiment 1, we have found similar outcomes in the Simon effect results for the visual task in typically developed children. Moreover, our findings collimate with two other studies that have examined the Simon effect in the visual modality with the crossed posture during childhood (Crollen et al., 2015; Crollen & Noël, 2015). Therefore, we can conclude that, as hypothesized, in typically developed children, the external spatial frame might maturate with the same developmental steps in visual and auditory modalities. We have to highlight that we used different eccentricities between auditory (90°) and visual (10°) tasks. We chose these values because, in our paradigm, spatial information was irrelevant, and we needed that for the children, there was no difficulty or doubt in whether the stimuli were left or right. Because the visual and auditory systems have very different localization abilities (Odegaard et al., 2015), we used very lateral stimuli for audio so that the lateral localization of the lateral source would be clear for all children. In contrast, the visual eccentricity was chosen so that the stimulus would be lateralized but at the same time remain in the fovea, to make sure that even visually impaired children could perceive them. As there were no differences in the Simon effect between auditory and visual stimuli, we believe that the difference in eccentricity did not affect the task.

In Experiment 2, we found that vision impairment affects the development of the external spatial frame in the visual modality but not in the auditory modality. Specifically, the low-vision children showed the Simon effect in the uncrossed position, but not in crossed posture, whereas there was no difference between the two postures in the auditory modality. Furthermore, these results cannot be explained by the difference in age. These findings suggest the lack of an active role of vision in acquiring a fully mature spatial competence in the other senses, given that low-vision children showed similar performance to sighted children in the auditory task. If so, these findings appear to be in contrast with the literature, in which only two studies assess auditory-spatial abilities in low-vision children to the best of our knowledge. In one of these extant studies, the authors found impaired performance for low-vision children in an auditory localization task and no difference in blind children's performance (Cappagli & Gori, 2016). However, in a following study, the same authors found that low-vision children performed even better than sighted peers in a dynamic sound localization task while the blind group showed an impaired performance (Cappagli, Finocchietti, Cocchi, & Gori, 2017). In our study, the spatial information was implicit and irrelevant to the performance, while sound localization requires responding actively to the spatial input. It may be that these two tasks rely on different abilities of spatial competence. Moreover, it could be that different kinds of stimuli and tasks influence spatial performance differently. Finally, we must highlight that we selected a rooster and a hen as stimuli that could bring similar sounds and visual information. Moreover, we opted for a consistent association of animal and color in the visual task to help the visually impaired participants, as explained in the methods session. These choices could have affected the results of low-vision children. However, as the accuracy level in the congruent trials with uncrossed hands posture was relatively high (>90%) and similar to sighted children for both auditory and visual tasks, we can conclude that these variables had a minor confound effect (see online supplemental materials for the analysis on accuracy).

In Experiment 3, we tested how the absence of vision from an early age influences the development of external coordinates. Since spatial competence in sighted children develops by means of the association between visual input and the execution of movements (Bremner et al., 2008), we hypothesized that blind children could not rely on this association to represent the space, especially for what concerns the external spatial frame. In our hypothesis, the absence of this association would also impact the other modalities. Our results revealed that in blind children also, auditory performance is impaired. Indeed, we found that, contrary to their sighted peers, blind children show a difference in the Simon effect between uncrossed and crossed postures. These results reveal the causal role of visual input in guiding the external spatial reference frame acquisition in the other sensory modalities. The difference between the performance of low-vision and blind children in the auditory task can be explained by considering the difference between the sensory feedback available with a total or partial absence of visual input. Low-vision children can still benefit from the association between vision and body movements, although the visual information is impaired (Cappagli et al., 2019). This means that the residual vision is sufficient to calibrate spatial performance in the auditory system, at least for what concerns the external spatial frame. On the other hand, the complete absence of sight at an early age prevents the possibility of associating visual and motor stimuli, resulting in a general impoverishment of spatial competence. For instance, as previously discussed, these results are in line with studies that found that blind but not low-vision children showed impaired localization abilities. At the same time, children with residual vision had compensatory mechanisms that allowed delivering even better performance to their sighter peers (Cappagli, Finocchietti, Cocchi, & Gori, 2017).

These results cannot be explained by the difference in age. Indeed, in Experiment 1, we have demonstrated a reduction of the Simon effect with age in typically developed children. This reduction is related to the maturation of the ability to resolve conflict, which reduces the interference effect, and reaches adult-like levels between 6 and 10 years old (Cao et al., 2013; Davidson et al., 2006). The absence of the effect of age in visually impaired children may indicate a lack of developmental progress, but we cannot state if this is a delay and if children can reach their peers' level at a later stage. A similar paradigm has been administered in early-blind adults with contrasting results. Specifically, Röder et al. (2007) found a reverse Simon effect (e.g., internal coordinate system used instead of external) in early-blind adults, suggesting that an external deficit persists in visually blind people into adulthood. However, when Crollen et al. (2017) repeated the same paradigm but modulated how to respond, they found that blind adults did not show internal coordinate use but a decrease of the Simon effect as in our Experiment 3. Moreover, the absence of the age effect could be explained in terms of variability; indeed, the outcome of visually impaired children is more variable compared with sighted children. As mentioned above, this variability may represent the relationship between brain plasticity and individual variability, resulting from different life experiences and rehabilitative interventions.

To conclude, our findings show there is a gradual maturation of the spatial reference frame during development when the visual input is available. In this maturation, vision calibrates other senses to process spatial information when the visual experience is available at birth. In contrast, other sensory modalities are not trained to encode external properties of the environment when vision is absent from birth (Vercillo et al., 2016). Our results reveal that vision has a causal role in guiding and calibrating the development of spatial reference frame in the brain even when VA is poor, as shown by low-vision children's performance. Furthermore, the results suggest that visual calibration of spatial perception in the first years of life is crucial for developing an external spatial frame. Vision and auditory modalities might mature in parallel with similar developmental steps when the visual inputs are fully available from birth. Finally, these findings may have an impact on developing assessment and practical rehabilitation training to compensate for the deficits experienced by visually impaired children. Notably, based on our results, blind children seem to need external audio-spatial calibration to compensate for the absence of vision. For example, it has been suggested that the association between movement and the resulting change in the auditory scene (i.e., audiomotor loop) may drive compensatory calibration in blind people (Lewald, 2013). In this view, some audiomotor tools have been proposed for assessing and rehabilitating spatial abilities in blind children and adults (Cappagli, Finocchietti, Baud-Bovy, et al., 2017; Esposito et al., 2021; Martolini et al., 2022). The results of these studies are in line with our results and evidence the necessity of early assessment and early intervention on residual abilities in visually impaired children to restore or rehabilitate impaired aspects of spatial perception.

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