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Assessment of spatial reasoning in blind individuals using a haptic version of the Kohs Block Design Test

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ABSTRACT

Past research investigating the spatial abilities of visually impaired people, provided conflicting results. There is thus an urgent need to develop standardized tests for the evaluation of spatial cognition when vision is absent or disrupted. To this aim, we developed a haptic version of the Kohs Block Design Test and investigated the spatial non-verbal reasoning of early blind, late blind and sighted individuals. Participants reproduced 3D printed haptic configurations by assembling blocks with different textures, within a time limit. Results showed that early blind individuals reproduced fewer haptic designs than the other two groups correctly. Instead, the assembling time of the correct responses was similar among all groups. Moreover, blindness duration (in years) did not seem to affect the correctness of the performance: no significant correlation between the two variables was observed for early and late blind participants. Since only early blind individuals display difficulties in mentally representing the haptic configurations and manipulating multiple spatial information, we conclude that early visual deprivation may affect spatial reasoning capabilities. The present study adds new insights on the role of visual experience in the development of spatial skills and represents a first step in the adaptation of standardized tests for the assessment of spatial cognitive abilities in visually impaired people.

1. Introduction

Representing and manipulating spatial information is a highly demanding task that is part of everyday life. Understanding the impact of blindness on these abilities is of fundamental importance to promote visually impaired individuals' autonomy and well-being.

A large body of research has defined vision as the most accurate sense to elaborate space (Alais and Burr, 2004). It was principally because the visual system allows the brain to acquire and process detailed spatial information and the simultaneous perception of the environmental proprieties as a whole (Thinus-Blanc and Gaunet, 1997). Studying blindness permits investigating this sensory dominance and understanding vision's influence on acoustic and tactile spatial abilities development. Past researches highlighted conflicting results regards this topic. For example, some studies reported enhanced auditory spatial abilities of blind individuals in localizing sound sources in the horizontal domain (Lessard et al., 1998; Röder et al., 1999; Voss et al., 2004). However, this superiority is not always confirmed when it comes to localizing moving sounds (Finocchietti et al., 2015; Vercillo et al., 2017) and detecting acoustic stimuli in the vertical plane (Lewald, 2002; Voss et al., 2015; Zwiers et al., 2001). Similar results have been reported for the haptic domain. Visually impaired people can generate mental images of tactile spatial layouts, but their performance drops when asked to manipulate them actively or to retain multiple spatial configurations simultaneously (Cattaneo et al., 2007; Vecchi, 1998; Vecchi et al., 2004).

Moreover, blind and sighted individuals show similar mental rotation skills when asked to compare two haptic figures. Indeed, their response time increases as a function of the rotation angle of one of the two configurations (Carpenter and Eisenberg, 1978; Marmor and Zaback, 1976). Nevertheless, in this task, early blind individuals appeared to be slower and less accurate than sighted controls, revealing that the absence of visual experience still has a cost in some spatial skills. Fortin et al. (2006) found similar results in a study that used a tactile map to evaluate early blind, late blind, and sighted people's topographic orientation skills. Visually impaired participants showed orientation abilities similar to sighted controls, but early blind individuals made more errors when mental rotation skills were required to perform the task (Fortin et al., 2006).

An observation adding complexity to this debate is the role played by the onset of the visual impairment. Some studies revealed that late compared to early blind individuals report enhanced spatial abilities in

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Table 1
Clinical details of visually impaired participants.

Participant	Age	Gender	Pathology	Blindness onset	Residual vision	Years Braille reading
EB1	32	F	Retinopathy of prematurity	Birth	No vision	26
EB2	20	F	Retinopathy of prematurity	Birth	Light and shadows	15
EB3	27	M	Leber Amaurosis	Birth	No vision	21
EB4	26	F	Congenital glaucoma	Birth	No vision	20
EB5	46	M	Atrophy optic nerve	Birth	No vision	40
EB6	52	M	Unknown	Birth	Light and shadows	49
EB7	30	F	Retinitis pigmentosa	Birth	Light and shadows	25
EB8	28	F	Bilateral microphtalmia	Birth	Light and shadows	22
EB9	42	F	Microphtalmia with congenital cataract	Birth	No vision	35
LB1	54	F	Leber Amaurosis	46 y.o.	No vision	48
LB2	59	F	Retinitis pigmentosa	40 y.o.	Light and shadows	None
LB3	31	M	Corneal opacity	12 y.o.	No vision	25
LB4	40	F	Retinitis pigmentosa	30 y.o.	Light and shadows	19
LB5	67	F	Retinitis pigmentosa	32 y.o.	Light and shadows in right eye, no vision in left eye	45
LB6	59	M	Uveitis	10 y.o.	Light and shadows	49
LB7	29	M	Leber Amaurosis	18 y.o.	Light and shadows	13
LB8	54	F	Retinitis pigmentosa	30 y.o.	Light and shadows	None
LB9	31	M	Degenerative oculopathy	18 y.o.	Light and shadows	19

EB: early blind, LB: late blind, M: male, F: female.

mental imaging and orientation tasks (Cattaneo et al., 2008; Fortin et al., 2006; Hollins and Kelley, 1988). This result suggests that the lack of vision in the first years of life determines the spatial impairment emerged in blindness. However, it is worthy to note that other studies reported a spatial impairment also in late blind performance (Amadeo et al., 2019; Monegato et al., 2007).

Given these conflicting results, a comprehensive investigation about the nature of spatial cognition of people with visual impairment is further needed. In particular, it would be necessary to develop standardized tools to assess spatial organization and reasoning skills in case of visual impairment. For this purpose, we tested early blind, late blind, and sighted individuals with a haptic version of the Kohs Block Design Test (Kohs, 1920, 1923), a neuropsychological tool initially developed as a measure of non-verbal intelligence. We chose this test since it focuses the investigation on spatial reasoning, that is, the ability to estimate, mentally represent, and manipulate spatial information to solve a problem. Our version of the Kohs Block Design Test consists in 3D printed haptic configurations that the participant has to reproduce by assembling haptic blocks (previous adaptations of the test: Ohwaki et al., 1960; Reid, 2002; Suinn et al., 1966; Thiebaut et al., 2002; for a review see: Mazella et al., 2014).

Considering the impact mentioned above of blindness on spatial skills, we expected to observe different performances in the test between blind and sighted participants. Moreover, by comparing early and late blind individuals, we could keep the influence of blindness onset and blindness duration on the abilities to representing and manipulating spatial information.

2. Material and methods

2.1. Participants

In this study, we recruited 36 participants: 18 blind (BL, 11 women, mean age ± SD: 40.91 ± 14.26 y.o., range 20–67 y.o.) and 18 age-matched sighted individuals (SC, 9 women, mean age ± SD: 40.12 ± 14.96 y.o., range 18–65 y.o.). Regarding participants with visual disabilities, nine of them were early blind (EB, 6 women, mean age ± SD: 34.12 ± 10.52 y.o. age range 20–52 y.o) and nine late blind (LB, 5 women, mean age ± SD: 47.69 ± 14.70 y.o, age range 29–67 y.o). In all cases, visual impairment was attributed to peripheral deficits (i.e., deficits of the retina or optic tract), and blindness was total except for light perception in eleven of them (for clinical details, see Table 1). Sixteen participants were Braille readers, while two of them never received Braille training. Sighted controls had a normal or corrected-to-normal vision. None of the participants reported additional sensory disabilities or neurological problems. The study was approved by the ethical committee of the local health service (Comitato Etico, ASL 3, Genova) and conducted following the Declaration of Helsinki. All participants gave written informed consent before starting the test.

2.2. Material

In this study, we developed our haptic version of Kohs Block Design Test (Kohs, 1920, 1923) by adapting the Stanford-Ohwaki-Kohs Block Design Test For The Blind (Suinn et al., 1966).

We used 18 haptic designs and 16 haptic blocks made of 3-D printed plastic. Instead of the four fabrics used in the original version of the paradigm, in this study, we used only two textures to design the stimuli, in line with a more recent version of the test (Reid, 2002). The 18 haptic designs were abstract configurations composed of two colors and two textures: black areas with a rough texture and white areas with a smooth texture (Fig. 1A). Although participants never saw the blocks and designs, we printed them in different colors to help the experimenter check the correctness of the response.

The 16 identical blocks (3 cm x 3 cm x 3 cm) were composed of the same textures of the haptic design. Two faces of the cubes were white with a smooth texture, two faces were black with a rough texture, while the two remaining faces were divided in two along the diagonal: one half was black and rough and the other half white and smooth (Fig. 1B).

The haptic designs had different dimensions according to the number of blocks needed for assembling. We had ten designs composed of 2 × 2 blocks, two designs of 3 × 3 blocks and six designs of 4 × 4 blocks (Fig. 1A). The first and simplest design was used only to familiarize the participant with the test in a practice session.

2.3. Procedure

The experimental procedure followed the indications of the testing manual by Suinn et al. (1966). The task required participants to reproduce a haptic design by assembling the haptic blocks. The participants had to organize the position of each haptic block inside a sized plastic support included in the test material. Sighted participants were blindfolded while performing the task, and they were not able to see the test material before and during the experiment.

Participants were informed that for each design, they had a specific number of blocks to use and a limited time for assembling (see Table 2 for details). They could repeatedly explore the configuration while performing the task. After familiarizing with the test material,

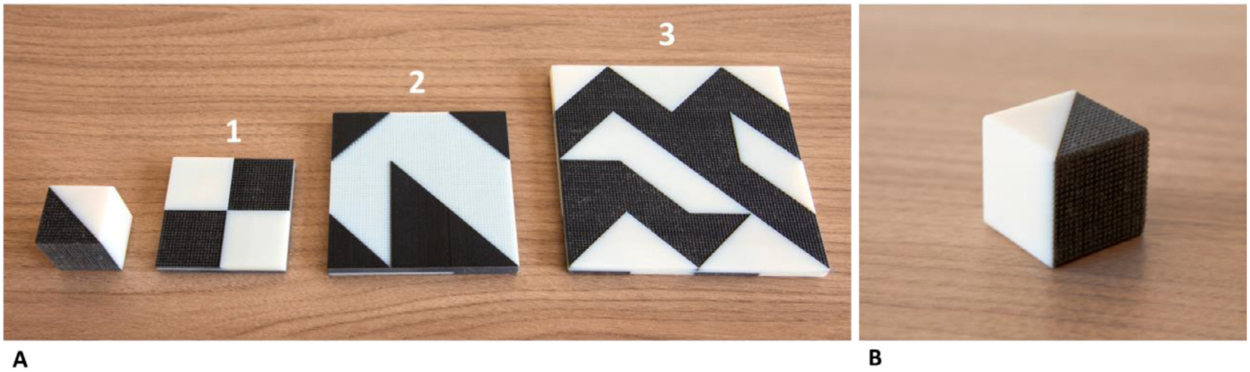

Fig. 1. Images of the test material. (A) Example of the three dimensions of the haptic designs. In relation to the size of the haptic block on the left edge of the image, 4 blocks are needed to compose haptic design 1, 9 blocks to compose haptic design 2 and 16 blocks to compose haptic design 3. **(B) One of the 16 identical haptic blocks.** In the picture, the faces of the cube that differ for color and texture are shown. Two faces of the cube are white with a smooth texture, two faces are black with a rough texture, and two faces are half black with a rough texture and half white with a smooth texture.

Table 2
The table shows, for each haptic design, the time limit in seconds within which the participant had to reproduce the haptic design and the number of haptic blocks needed for assembling.

Haptic design	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Time limits (s)	65	90	90	90	160	90	255	100	100	360	270	465	465	465	720	720	720
Blocks	4	4	4	4	4	4	4	4	4	9	9	16	16	16	16	16	16

participants were asked to assemble a practice design without a time limit, and when the practice design was correctly reproduced, the test started. For each configuration, the experimenter asked participants to complete the design as fast and accurately as possible. Haptic design assembling difficulty increased progressively depending on the configuration complexity and number of blocks to use.

For each design, we recorded the participants' assembling time starting when they began exploring the haptic configuration with their hands to the moment they self-reported the conclusion of the assembling. For the scoring, the reproduced design was considered correct if assembled without errors within the time limits, while it was considered incorrect if assembled beyond time limits and/or with composition mistakes. If the reproduced pattern was not correct, subjects could adjust their configuration, but the design was still considered incorrect. The test was interrupted after two consecutive incorrect designs (stop criterion). Thus the total number of reproduced designs per participant depended upon the subject's performance.

2.4. Data analysis

To test the general influence of visual impairment on the performance, we first compared sighted controls (SC) and all the blind (BL) participants, independently if blindness onset was late or early in life. In a second part of the analysis, we also explored the influence of blindness onset on task performance by dividing the blind participants into two groups: early blind (EB) and late blind (LB).

For each participant, we computed: *correctness* (i.e., the number of reproduced designs correctly assembled within the time limit) and *time bias* (i.e., the subject's assembling time normalized on the time limit of each haptic design). The *time bias* was calculated for the correct designs only.

Shapiro-Wilk normality test showed that both early blind and late blind groups were not normally distributed for *correctness* (EB: $W = 0.658$, p-value < 0.001; LB: $W = 0.732$, p-value $= 0.002$; SC: $W = 0.915$, p-value $= 0.106$), while all groups showed a normal distribution for *time bias* (EB: $W = 0.983$, p-value $= 0.978$; LB: $W = 0.929$, p-value $= 0.472$; SC: $W = 0.983$, p-value $= 0.976$). Therefore, the non-parametric Mann–Whitney test and Kruskal–Wallis test were computed to compare groups for the *correctness* variable. At the same time, *time bias* was analyzed by running two tails independent-samples t-tests and one-way ANOVA.

Moreover, for each experimental group, we computed a non-parametric Spearman correlation to assess the relationship between *correctness* and *time bias*.

Finally, to verify whether blindness duration affects *correctness* and *time bias*, we computed blindness duration in years. We ran two different ANCOVAs with Group (EB and LB) as a categorical variable and Blindness duration as a covariate. Given the violation of the normality assumption for *correctness*, we conducted a permutation ANCOVA on this variable. To compute the permutation test, we used the *aovp* function of the lmPerm package in R. A similar analysis was run with Age as a covariate.

Alpha level was set at 0.05 for all statistical analyses and Bonferroni correction was used for multiple comparisons.

3. Results

Statistical analyses on SC and BL groups revealed no significant differences for both *correctness* (Mann–Whitney test: $U = 209.5$, $z = -1.492$, p-value $= 0.135$, $r = 0.248$) and *time bias* (independent-sample t-test: $t(31) = -0.257$, p-value $= 0.798$, $d = 0.086$). Nevertheless, when splitting BL group accordingly to blindness onset, results on *correctness* showed a significant main effect of the group ($\chi^2(2, N = 36) = 11.945$, p-value $= 0.002$, $\epsilon^2 = 0.341$). Post hoc tests corrected for multiple comparisons revealed that EB group has significant lower scores compared to both LB ($U = 10$, $z = -2.695$, p-value $= 0.021$, $r = -0.635$) and SC ($U = 18.5$, $z = -3.202$, p-value $= 0.004$, $r = -0.616$) groups, suggesting difficulties in spatial reasoning tasks when blindness occurs early in life (Fig. 2). No significant difference in the *correctness* was found between the LB and SC groups ($U = 96$, $z = -0.749$, p-value $= 1$, $r = 0.144$). On the contrary, the one-way ANOVA on *time bias* did not show a significant group main effect ($F(2,33) = 1.74$, p-value $= 0.191$, $\eta_p^2 = 0.095$), revealing that blindness does not affect how quickly participants assembled the correct reproduced design (Fig. 2). Given the different results between *correctness* and *time bias* that emerged in the comparison among groups, we decided to explore the relationship between these two components by running a non-parametric Spearman correlation analysis. Results showed that *correctness* does not signif-

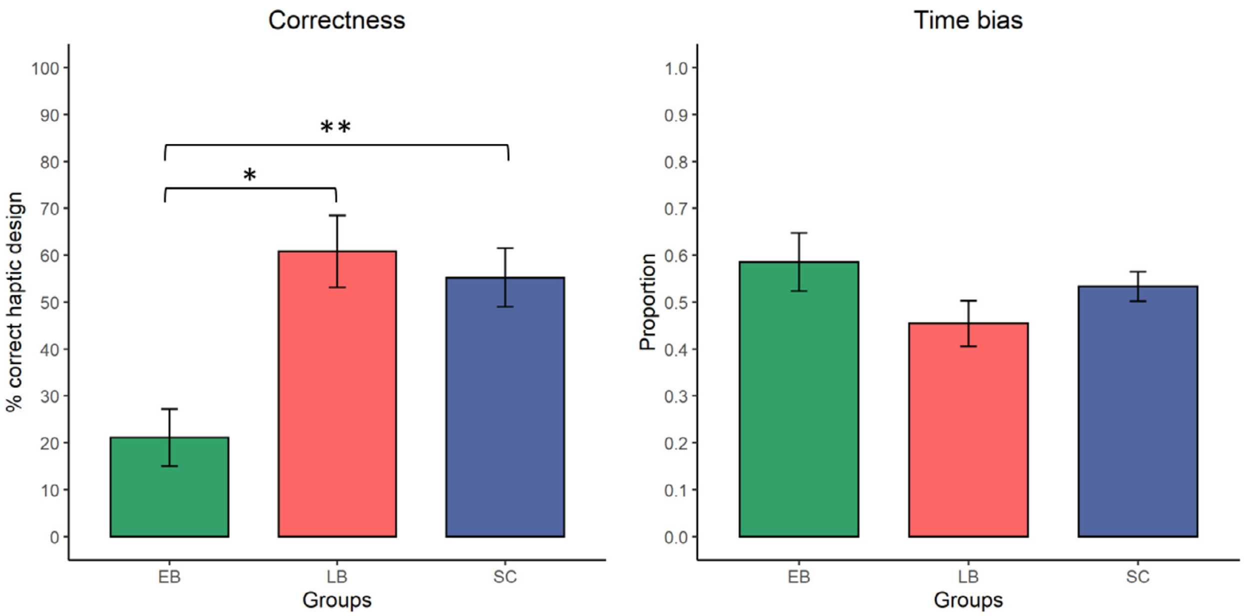

Fig. 2. Comparison among EB, LB and SC groups in the correctness and time bias. Left panel shows the percentage of haptic designs correctly reproduced on a total of 17 configurations; right panel shows the ratio between the subject's assembling time and the time limit of designs correctly reproduced. Error bars show standard error. Asterisks indicate significance level: * represents $p < 0.05$, ** $p < 01$.

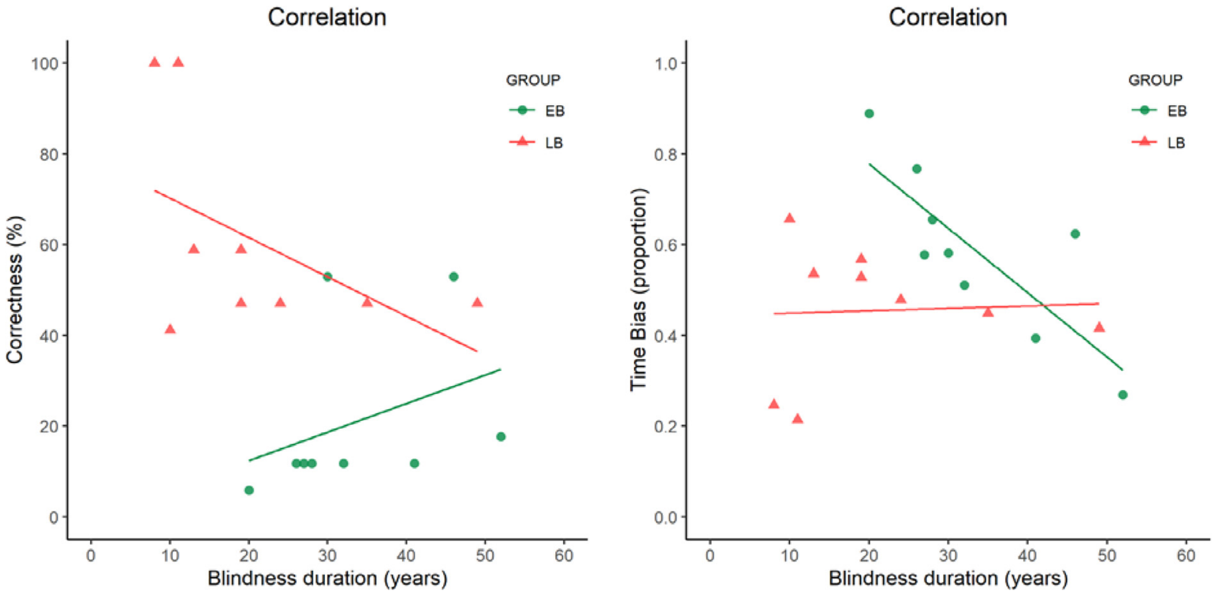

Fig. 3. Correlation of correctness and time bias with blindness duration (in years). The left panel shows the percentage of correctly reproduced designs against the blindness duration (in years spent without vision) for both visually impaired groups (EB and LB). Each data point represents one individual participant. For both groups, there is no significant correlation. The right panel shows the time bias against the blindness duration (in years spent without vision) for both visually impaired groups. Each data point represents one individual participant. Only the EB group reported faster assembling time associated with more extended periods of blindness duration, as confirmed by a significant positive correlation.

icantly correlate with *time bias* (SC: r_s= - 0.456, *p*-value = 0.170; LB: r_s= - 0.527, *p*-value = 0.434; EB: r_s= - 0.358, *p*-value = 1), meaning that slower participants are not necessarily less accurate. This observation minimizes the role of assembling time in test performance and emphasizes the role of mere spatial reasoning components.

Finally, to control whether the duration of blindness had an influence on test performance, we conducted a permutation ANCOVA on *correctness* that revealed only a significant main effect of Group (Group: Iter = 5000, *p*-value < 0.01; Blindness duration: Iter = 51, *p*-value = 0.784). In fact, for both visually impaired groups, the number of correctly reproduced design was not significantly correlated with the length of blindness duration (EB: r_s= 0.699, *p*-value = 0.080; LB: $r_s = -0.423$, *p*-value = 0.512), suggesting that the performance in the haptic Kohs Block Design Test is not influenced by the duration of the sensory deprivation (Fig. 3). An ANCOVA on *time bias* showed only a significant interaction between Group and Blindness duration (F(1,14) = 6.260, *p*-value = 0.025, $\eta_p^2 = 0.31$). In particular, a correlation analysis showed a significant negative correlation between *time bias* and Blindness duration in the EB group ($r_s = -0.766$, *p*-value = 0.031), but not in the LB group (r_s = - 0.050, *p*-value = 1) (Fig. 3). The same statistical analysis was computed with Age as a covariate. Permutation ANCOVA on *correctness* revealed a significant main effect of Group (Iter = 5000, *p*-value <0.05), but not of Age (Iter = 78, *p*-value = 0.564). In the analysis on *time bias* both main effects were not significant (Group: Iter = 170, *p*-value = 0.370; Age: Iter = 51, *p*-value = 0.941).

4. Discussion

The present study investigates spatial non-verbal reasoning of sighted, early blind and late blind individuals by using an adapted version of a well-established performance test, the Kohs Block Design Test. In our version of the test, participants had to reproduce abstract haptic configurations by assembling blocks based on haptic information only. Results reveal that (i) early blind individuals' performance was significantly lower compared to both late blind and sighted participants, underlining difficulties in mentally representing and manipulating spatial configurations through touch; (ii) the performance is related to early visual experience, rather than the duration of blindness; (iii) the correctness of the response seems not to be related to time performance.

The emergence of blindness in the first years of life affects spatial cognitive abilities investigated with the haptic version of the Kohs Block Design Test, both in the phase of the exploration and reproduction of the haptic configuration. Regarding mental representation and manipulation of spatial images in the absence of vision, literature presents mixed findings. On the one hand, previous studies have shown that blind people, similar to sighted individuals, can generate mental images conveyed by haptic (Aleman et al., 2001; Cattaneo et al., 2008; Kerr, 1983; Vecchi et al., 2004) or auditory (Setti et al., 2018) stimuli. On the other hand, early blind individuals, compared to both late blind and sighted participants, showed difficulties in other aspects of spatial cognition, such as the estimation of metrical spatial relationships (Afonso et al., 2010; Gori et al., 2014) and the simultaneous processing of multiple tactile elements (Vecchi et al., 2004). Interestingly, in a study by Vecchi et al. (2004), the authors tested congenitally blind individuals in different haptic tasks requiring the memorization and recall of single and multiple matrices or the integration of targets in a single matrix. The study showed that congenital blindness affects the ability to maintain simultaneously multiple spatial information, but not the sequential manipulation of spatial elements. This impairment has been attributed to the simultaneous nature of processing multiple items when visually conveyed, while haptic and auditory encoding is mostly based on sequential processing of sensory information. Thus, the different ways of acquiring and managing perceptual information influence how mental images are processed, determining different performance between sighted and blind individuals. Along these lines, here we observed a lower score for early blind participants compared to the other two groups. In our version of the Kohs Block Design Test, participants needed to manipulate simultaneously complex haptic information to generate and process multiple spatial representations. Moreover, in order to build a veridical mental image of the target haptic configuration, participants needed to understand the spatial locations and the metric relationships of the tactile elements composing the design. Early blind individuals may be able to generate a mental representation of the haptic design, but, contrary to sighted controls and late blind participants, their internal image likely does not maintain the physical metric information of the target configuration. In other words, the ability to process and retain the actual distances among the tactile elements of the design is compromised, thus providing an inaccurate mental reference template. Similar previous findings indicate that, in building mental representation of a scene, early blindness impacts on the ability to preserve topographic organization of spatial elements (Afonso et al., 2010). In addition, while executing the Kohs Block Design Test, the participant needs to constantly check the reproduced design, correct potential errors and update the mental representation of the adjusted configuration. Past research revealed that congenitally blind individuals, compared to both late blind and sighted people, show difficulties in updating spatial information of a haptic scene that has been spatially manipulated (Pasqualotto and Newell, 2007). In our study, this impairment may have led early blind participants to an inefficient "correction-updating" mechanism of the reproduced design, which suggests a strong impact of early blindness on the online spatial processing of haptic information.

Focusing on the effect of blindness duration on the performance, our study reveals that late blind participants show performances similar to sighted controls and dissimilar to early blind subjects. This result suggests that the lack of visual experience during the first years of life, rather than the absence of vision per se, affects spatial reasoning. Moreover, the absence of a significant influence of blindness duration on the performance supports the idea that blindness onset is the main aspect that determines the success in our version of the Kohs Block Design Test. These results are in line with previous studies reporting efficient spatial abilities of late blind individuals (Cattaneo et al., 2008; Hollins and Kelley, 1988), which may find an explanation in the so-called cross-sensory calibration theory. According to this theory (Gori, 2015; Gori et al., 2008, 2012), visual information in the first period of life calibrates the other sensory modalities to gain complex spatial abilities efficiently. Therefore, the visual experience of late blind individuals acquired during development may have determined the differences in the spatial reasoning abilities that emerged in our results. Accordingly, early blind individuals did not experience a sufficient period with vision to gain such visually driven spatial skills.

Time management does not seem to overall influence performance in the Kohs Block Design Test. While performing the task, participants were required to avoid exceeding each haptic design's temporal limit. Results showed that, on average, all groups needed a similar amount of time to assemble the correct haptic configurations. This suggests that all participants managed to perform the task within the time limits and that the speed of assembling likely did not influence the difference in performance observed between early blind individuals and the other two groups. The absence of correlation between time bias and correctness corroborates the independence of these two factors. For all groups, a more significant number of correct designs does not necessarily relate to faster assembling time, thus indicating that early blind individuals potentially show a poorer performance despite their ability to manage time. All these observations suggest that early blind individuals' performances may be primarily explained by their impaired spatial skills that overall led this group to reach the stop criterion of two consecutive incorrect designs early in time. However, previous studies showed that blind individuals are slower than sighted controls in mental rotation and spatial displacement tasks (Blanco and Travieso, 2003; Hollins and Kelley, 1988; Marmor and Zaback, 1976). These contrasting results may be due to differences in the nature of the task and the involved cognitive abilities. Thus the further investigation of the temporal aspect of spatial reasoning is needed.

5. Conclusion

By using a haptic version of the Kohs Block Design Test, we showed that the absence of vision during the first years of life affects the development of high-order spatial skills for which the functional richness of vision seems to be essential. These results are in line with a body of studies that report impaired spatial processing in people who are blind since birth or early in life (Gori et al., 2014, 2018; Vercillo et al., 2017, 2018). Besides, we believe that the high versatility and the wide range of abilities investigated by the Kohs Block Design Test used in our study make this test a valid tool to complete the cognitive assessment of people with visual disabilities. Having access to a variety of assessment tools is of fundamental importance to define weaknesses and strengths of cognitive functioning in people with visual impairment, for example, while attending rehabilitation programs and/or Orientation and Mobility training. For this purpose, a future standardization of the haptic adapted test (that involves both blind and low-vision individuals) is suggested.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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