The Effect of Programmable Tactile Displays on Spatial Learning Skills in Children and Adolescents of Different Visual Disability

Fabrizio Leo, Elena Cocchi, and Luca Brayda

***Abstract*— Vision loss has severe impacts on physical, social and emotional well-being. The education of blind children poses issues as many scholar disciplines (e.g., geometry, mathematics) are normally taught by heavily relying on vision. Touch-based assistive technologies are potential tools to provide graphical contents to blind users, improving learning possibilities and social inclusion. Raised-lines drawings are still the golden standard, but stimuli cannot be reconfigured or adapted and the blind person constantly requires assistance. Although much research concerns technological development, little work concerned the assessment of programmable tactile graphics, in educative and rehabilitative contexts. Here we designed, on programmable tactile displays, tests aimed at assessing spatial memory skills and shapes recognition abilities. Tests involved a group of blind and a group of low vision children and adolescents in a four-week longitudinal schedule. After establishing subject-specific difficulty levels, we observed a significant enhancement of performance across sessions and for both groups. Learning effects were comparable to raised paper control tests: however, our setup required minimal external assistance. Overall, our results demonstrate that programmable maps are an effective way to display graphical contents in educative/rehabilitative contexts. They can be at least as effective as traditional paper tests yet providing superior flexibility and versatility.**

***Index Terms*— Blindness, learning, rehabilitation, spatial ability, tactile displays.**

I. INTRODUCTION

ALTHOUGH different studies showed that lack of vision does not impede the ability to process and transform mental images (see, for review, [1]), a consistent body of knowledge demonstrated how blindness can have a negative impact on spatial cognition and on imagery abilities (see, for reviews, [1], [2]). For instance, studies investigating spatial memory when visual impairment occurs showed deficits in blind people. These deficits were found at least in tasks requiring either a simultaneous retention of two separate spatial configurations or an active manipulation of a memorized matrix [3], [4]. The causes of these deficits are still debated. Deficits in spatial performances might be due to visual deprivation or to more exogenous variables such as a lack of active interaction with the environment (e.g., [5]). On the other hand, recent evidences highlight the role of vision in spatial imagery (e.g., [6]). Visuo-spatial imagery seems to play a role also in tactile pictures recognition, particularly for complex tactile pictures representing common objects [7]. Nevertheless, some studies did not find substantial differences in tactile picture recognition between sighted and blind participants (see, for review, [7], [8]), even though blind people may benefit from specific instructions when complex representations of 3D objects are rendered [8]. Brain signals linked to cognitive maps developed from virtual tactile objects seem to be developed independently on vision capabilities [10], [11]. Other evidences showed even superior tactile recognition ability in late blind compared to sighted or congenitally blind people [9], [12]. On the other hand, it is well known how dealing with geometrical concepts is a big issue in educative contexts in blind persons. Learning geometry seems to be especially difficult because of the lack of understanding of many spatial concepts especially in congenitally blind [13], [14]. As a matter of fact, in some European schools located in Norway and Cyprus, blind students can get exemptions for geometry classes since teachers consider as almost impossible to teach them geometry [13], [15]. However, the development of spatial skills in visually impaired students can be facilitated by providing teachers and rehabilitators with knowledge and methods to create teaching support tools [16]. Current standard approaches exploit the sense of touch. Textured materials, thermoformed surfaces or swell paper hosting Braille dots or raised lines are generally used to identify tactile pictures as two-dimensional representations [17]. However, these methods present several limitations. First of all, they allow neither to present information dynamically nor to easily adapt it to the single user needs. Secondly, the presentation of fixed tactile patterns often requires the presence of a support person assisting the student. Finally, producing raised-lines papers is expensive. To address these issues, several technological approaches have been proposed either using tactile displays [18]–[25], haptic interaction technologies [26], [27] or haptic vibrational feedback coupled with mobile devices [28], [29].

Our study is aimed at investigating whether visually impaired children and adolescents can understand and take advantage of tactile graphics presented using a programmable pin-array tactile display. Pin-array displays have shown to be

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effective means of conveying tactile graphics on both sighted persons and blind adults [22], [24], [30], [31]. However, to our knowledge this technology has rarely been tested using learning paradigms in visually impaired children varying in age and degree of visual disability. The latter is certainly a major limitation since visually impaired youngsters are an extremely heterogeneous group [13] and different degrees of visual impairment can result in different imagery, spatial and tactile acuity performances [12], [32]–[35]. A previous study [36] showed a learning effect in visually impaired middle school students using math and science apps. However, only four students were recruited in that study and they did not use a pin-array display but a haptic force-feedback device [36].

In our study, by mean of a pin-array tactile display we implemented a four-sessions training using two tests designed to require spatial abilities: a spatial memory task inspired by Vecchi et al. work [3] and a geometrical shapes recognition task. Our hypothesis is that youngsters performances in those tests can improve during the training. The tests used minimal assistance from rehabilitation practitioners.

Another aim of the study is to compare the effectiveness of pin-array tactile displays with the state-of-the-art in education and rehabilitation of visually impaired people, that is raised-line drawings. To do so, we implemented different tests on paper, which however involve similar cognitive functions and skills (e.g., spatial memory, tactile shape discrimination) to those required to perform the tests on their technological counterpart. We investigated youngsters learning during the training also with the paper tests. Our hypothesis is that programmable pin-array tests can elicit learning effects at least as effective as those obtained by traditional procedures employing swell paper. Furthermore, the paper tests were administered twice in each session, that is before (pre-tests) and after (post-tests) programmable pin-array tests. We employed this design to investigate whether we could observe a within-session learning effect.

Finally, we wanted to investigate whether learning effects change as a function of the degree of visual disability and/or the age of youngsters. Hence, we tested two different groups of participants: one group of blind and one group of low-vision youngsters. Youngsters age spanned from 6 to 22 years. Since we decided to adapt the level of difficulty of tests at the baseline according to the ability of the participant, we expect that all the participants could improve their performances regardless of age and degree of visual disability.

II. METHODS

A. Participants

Sixteen visually impaired children and adolescents (five males) took part in the study. Eight of them were legally blind and eight had low vision. Seven youngsters of the legally blind group were totally and congenitally blind. Blind participants age ranged from 8 to 22 years (mean age 12.6). Low vision participants age ranged from 6 to 14 years (mean age 11.8). All participants had no conditions affecting tactile perception. Table I summarizes the characteristics of the participants. The sample was selected by the Rehabilitation Institute for Blind People Istituto David Chiossone onlus in Genoa, which also hosted the experiments. Participants gave informed consent in accord with the Declaration of Helsinki. The experimental protocol was approved by the local Ethics Committee.

TABLE I

CHARACTERISTICS OF THE PARTICIPANTS INCLUDING GENDER, AGE, AETIOLOGY, AND AGE AT ONSET OF VISUAL IMPAIRMENT AND EVENTUAL RESIDUAL VISION

Participant	**Gender**	**Age (y)**	**Aetiology of visual impairment**	**Age at onset of visual impairment**	**Residual vision**
Legally blind					
01	F	9	Retinopathy of prematurity	birth	none
02	F	13	Congenital cataract	birth	none
03	F	16	Retinopathy of prematurity	birth	none
04	F	11	Retinopathy of prematurity	birth	none
05	M	12	Amaurosis	2 y	sense of light
06	M	8	Retinopathy of prematurity	birth	none
07	F	10	Retinopathy of prematuriy	birth	none
08	F	22	Congenital glaucoma	birth	none
Low vision					
09	M	6	Albinism	birth	1/10
10	F	14	Arachnoid cyst	11 y	1/50
11	M	14	Gliomatosis cerebri	1 y	1/25
12	F	9	Microphthalmia	birth	2/12
13	M	12	Albinism	birth	3/20
14	F	13	Stargardt disease	birth	1/10
15	F	12	Homocystinuria	birth	1/20
16	F	14	Nystagmus	birth	1/10

B. Materials and Procedure

The two groups of blind and low vision youngsters performed a 4-sessions training. Participants with some residual sight were blindfolded in order to exclude any influence due to visual inspection of the experimental setup. In each session youngsters performed four different tests. We manipulated the test modality. More specifically, two tests were done using raised-line paper drawings and two using programmable tactile displays. Raised-line drawings tests were repeated twice in a session, that is before and after the programmable tactile displays tests. Before starting the actual tests participants familiarized with the test materials. The level of difficulty of the test with the programmable tactile display was adjusted at the beginning of the first testing session according to the youngsters' ability. In particular, the criterion was to find a

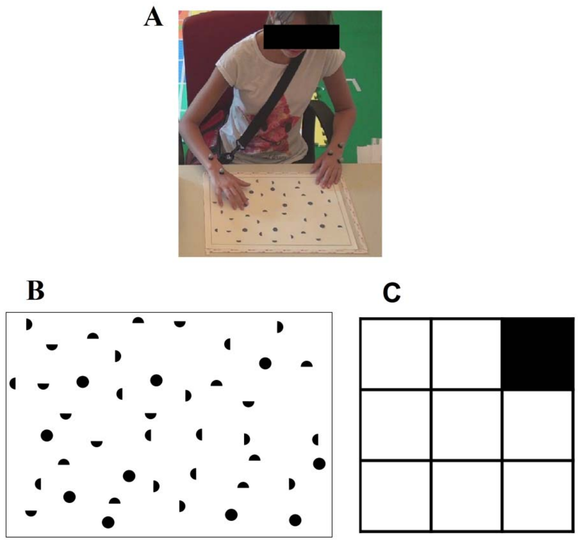

Fig. 1. A: Child performing the tactile symbol recognition test. B: Tactile symbol recognition and enumeration in noise test. C: Memory spanning of sequences of tactile symbols test.

performance target level of 70% of accuracy which represented first session baseline. This level ensured that the tests were neither too easy nor too difficult, while preserving the possibility to observe performance enhancements across sessions. After establishing the level of difficulty we started the tests. Importantly, we counterbalanced the order of programmable tactile display tests across sessions. A detailed description of all the tests follows below.

C. Tests With Raised-Lines Drawings

Raised-line drawings were produced using capsule paper treated with a heater (Konica Minolta Holdings Inc.).

1) Paper Spatial Test: Tactile Symbol Recognition and Enumeration in Noise: Youngsters were presented with an A3 raised-line drawing (see Fig. 1 A and B). There were two sheets, each one with a different disposition of circles: since sheets were presented twice in a session, this avoided repetition effects. For each sheet of paper, there were 10 circles embedded among 32 semicircle distractors. Circles diameter was 1.7 cm. The participants were asked to find as many different circles as they could in a limited time (30 s). We specified that circles must be counted only once. Therefore the test measured the ability of distinguishing and enumerating specific tactile symbols in specific regions of a desktop space. We measured the speed in recognizing the symbols in circles/second. Whenever necessary we reduced presentation time to avoid participants could find all the circles (times range used: 15–30 s; 5-s steps): in particular, if the participant counted all 10 circles within the time limit, we reduced the time limit in the next session; otherwise we waited the time limit to elapse.

2) Paper Spatio-Temporal Test: Memory Spanning of Sequences of Tactile Symbols: This test could be considered as a modified tactile version of the Corsi block tapping task [37]. We prepared a series of A4 sheets. Each A4 sheet of paper contained a centered 3 × 3 grid in relief (using the same printing technique as the previous exercise), depicted in Fig. 1 C. The grid size was 12.5 × 12.5 cm. The squares composing the grid had 4.2 cm side. All but one square composing the grid were empty. Each sheet of paper had a relief square in a different position (see Fig. 1 C for example with a top-right relief square). At the beginning the participants were presented with an entirely empty grid to learn the reference system. Then, participants were presented with a grid in which only one square was in relief and were asked to memorize its position on the grid. They were then presented with an entirely empty grid again and were asked to touch all the locations that previously contained the squares. Then the experimenter increased the sequence by adding a new square and we iterated the test by keeping the same sequence until the first mistake. Importantly, participants had to indicate the squares in the same order in which they were presented before. We measured the longest square sequence each youngster was able to report without any mistake (10 squares as recorded maximum).

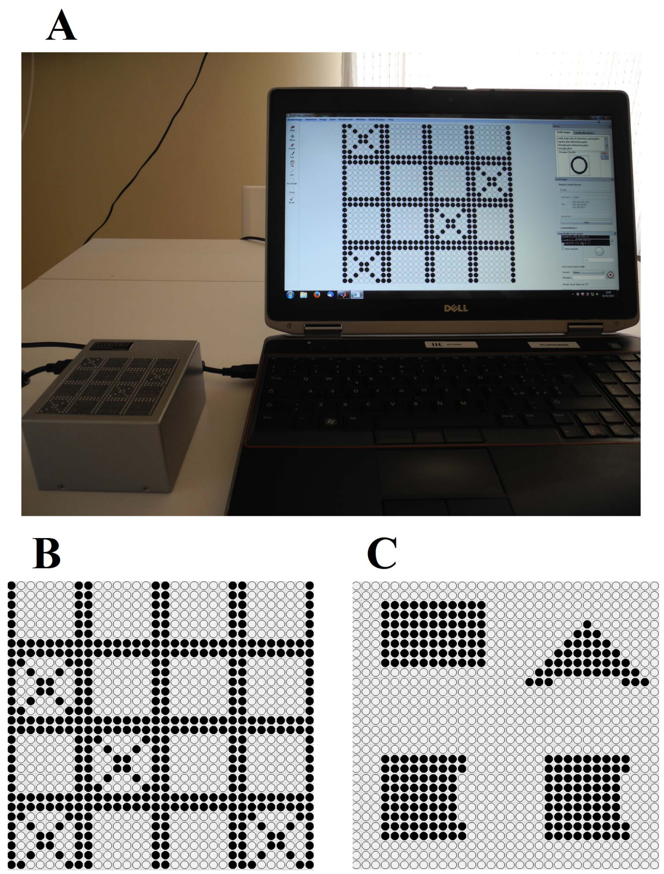

Fig. 2. A: Experimental setup with the Hyperbraille display on the left side and the PC running PadDraw software on the right side. Picture shows an example of trial of the spatial memory test. B: Spatial memory test with a 4×4 matrix and 4 targets. C: Shapes recognition test with a rectangle (top-left) as target and three distractors.

D. Tests With Programmable Tactile Displays

The tests were performed using a Pin-Matrix display (see Fig. 2 A) named Hyperbraille. It is a multi-line Braille display provided by Metec AG, composed by an array of 30 by 32 pins and screen refresh of 5 Hz. The display

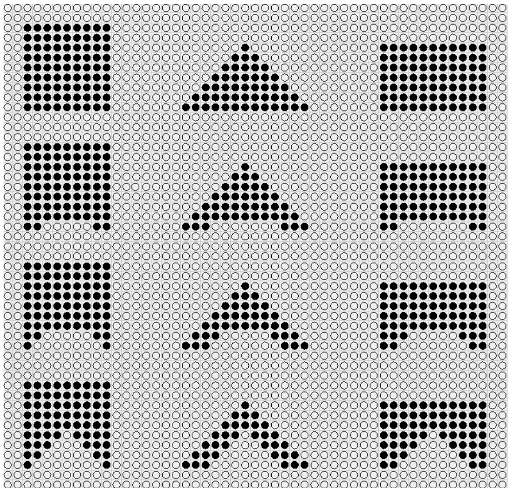

Fig. 3. Possible geometrical shapes of the shapes recognition test. The first row from the top shows the three possible canonical shapes. The rows from the second to the fourth show the possible distractors. Each row from the second to the fourth shows one of the three possible levels of difficulty of distractors in decreasing order (3,2,1).

area is composed by a large number of assembled pins, from novel vertical cells (each cell has 2 by 5 pins) at an equidistant resolution of 2.5 mm for each pin. Each pin could raise at about 0.7 mm. Being a pin equivalent to the tactile counterpart of visual discrete digital elements (pixel), we will call it from now on with the functional name of *taxel* [38]. The device was connected via USB cable to a standard PC and controlled by the software PadDraw, Matlab R2014 and Psychtoolbox 3.0.11 [39], [40]. PadDraw is a software developed by Geomobile GmbH for the FP7 EU Blindpad project [41].

1) Programmable Spatial Test: Geometrical Shapes Recognition and Localization in Noise: Youngsters were presented with four shapes on the Hyperbraille, one for each quadrant of the display. One of these shapes was a canonical geometrical figure whereas the other three shapes were distractors and resembled the canonical geometrical figures but had a distorted side (see Fig. 2 C for an example with a rectangle as geometrical shape surrounded by three distractors). The possible canonical geometrical shapes were three: a square, a rectangle or a triangle. The square size was 2 cm. Rectangle sides were 2.5 × 1.5 cm long. The longest side of the triangle was 3 cm with a height of 1.5 cm. Each canonical shape had three corresponding distractors (see Fig. 3 for a view of all the possible canonical shapes and distractors) of increasing level of difficulty. The difficulty was represented by the degree of similarity between the distractors and the canonical shapes. Difficulty level was set according to youngster ability: in particular, we started with the easiest level of difficulty (weaker similarity between canonical shapes and distractors) and we proceeded increasing the level of similarity between shapes until the participant made the first errors. At the end of this threshold estimation procedure, the actual test started. The participants were asked to verbally recognize the canonical shape (e.g., "rectangle", as in Fig. 2 C) and to report in which quadrant it was presented (e.g., "bottom-right"). We ran 10 trials of this test. We assigned 0.5 point for each correct shape recognition and 0.5 point for each correct shape localization. Whenever required we also reduced the presentation time of the shapes (range used: 4–30 s). This was done to avoid participants boredom in case they were much faster than the default shapes presentation time. If a youngster reached a ceiling effect (i.e., accuracy of 100%) during a testing session, we proceeded increasing the level of difficulty.

2) Programmable Spatio-Temporal Test: Memorization of Spatial Dispositions: Participants were presented with a N × N matrix on the Hyperbraille. The cells composing the matrix were separated by two raised lines of taxels (see Fig. 2 B). There were three possible matrix sizes: 2 × 2, 3 × 3 and 4 × 4 (see Fig. 2 B for an example of 4 × 4 matrix). Square size was 3.4, 2.2, and 1.6 cm in the 2 × 2, 3 × 3 and 4 × 4 conditions, respectively. Some of the squares composing the matrix contained a target, an 'X' symbol (see Fig. 2 B). The matrix was displayed to the youngster for 15 s. After this temporal interval, the targets disappeared and participants were asked to touch the squares that contained the targets. As in the previous test, we manipulated the level of difficulty. Hence, the matrix size and the number of symbols were set according to youngster ability: in particular, we started providing a 2 × 2 matrix with one symbol, then increased the number of symbols up to (N × N)/2 number of symbols. If the youngster still exhibited ceiling effects (i.e., a recall accuracy of 100%) we increased the matrix dimensions with one symbol. If we reached the maximum number of targets for a specific matrix size (e.g., 4 targets with a 3 × 3 matrix) and a participant still exhibited a ceiling effect, we proceeded increasing matrix size (e.g., 4×4) and reiterated the procedure up to a threshold when the subject made the first errors. At the end of this threshold estimation procedure, the actual test started. We ran 10 trials of this test. We computed the recall accuracy in percentage, that is the overall number of correctly recalled targets divided by the number of presented targets. The measure therefore excluded false positives (i.e., targets who were thought to be part of the matrix but which were actually not) but was sensitive to false negatives (i.e., targets which were actually part of the displayed matrix, but which were not recalled by the person). Also in this case, if a youngster reached a ceiling effect during a testing session, we proceeded increasing the level of difficulty.

Each test on the display was functionally linked to the corresponding paper test: a *geometrical shape recognition and localization in noise test* was linked to the *tactile symbol recognition and enumeration test* on paper, while a *memorization of spatial disposition test* was linked to the *memory spanning of sequences of tactile symbols*. At the end of each programmable tactile displays test we asked participants the following three questions.

1) How much difficult was the task on a 0–10 scale? (Perceived Level of Difficulty, PLD); this scale has shown to reflect cortical activity related to visuo-spatial cognitive load [10]
2) How well you think you did? (Perceived level of PErformance, PPE: depending on the task we asked to participants how many targets they thought they correctly recalled out of the total number of presented targets or

how many shapes they correctly recognized out of the total number of trials); this measure was already adopted when assessing tactile devices in [42]

3) How much are you tired on a 0–10 scale?

All the sessions were videotaped in order to measure the time required to complete each trial and the manual exploratory procedure used by each participant. A rehabilitation practitioner was always present next to the youngster while performing the tests.

III. RESULTS

Regardless of the test type, all the data were normalized to the first session baseline, i.e., were converted to percentage performance differences relative to the first session baseline (which was then set to 0). That means that for each of the three sessions following the baseline, the relative score of a single participant up to that session was computed as:

$$rel\_score_I = 100^* \sum_{i=1}^{I} \frac{abs\_score_i^{D_i} - \gamma}{\gamma}; \quad where$$
$$\gamma = abs\_score_{i-1}^{D_i} \tag{1}$$

where I ={2, 3, 4} runs across sessions, starting from the second, $abs\_score_{i-1}^{D_i}$ is the absolute performance of the test at session i, with the difficulty of that specific session D_i. In practice, the second session was expressed in terms of the improvement relative to the score of the first session, the third cumulated the improvement with respect to the second session and to the first, the fourth cumulated the relative improvements of all previous sessions. Note that change in performance can be negative. If the difficulty increased during a session, the relative improvement of the next session was referred to the initial score of the test with that new increased difficulty. In this way we were able to cumulate relative improvements related to serious games with different difficulty levels. This sometimes led to relative scores higher than 100%. As most data distributions were not normally distributed as verified with Shapiro-Wilk tests, we used non-parametric statistics.

A. Results with Raised-Lines Drawings

We tested the hypothesis that spatial abilities, represented by one distribution of individual relative scores per session [according to (1)], computed on all participants, could significantly increase across sessions. For each test and group we ran a Friedman ANOVA with Session (from first to fourth) as factor to verify whether the differences in performance between sessions were significant. Whenever required, we ran Wilcoxon matched pairs tests as post-hoc analyses. Then we tested the hypothesis that visual impairment could be a factor in how spatial abilities evolve across sessions: we then contrasted groups performances for each session (from the second to the fourth) in all tests using Mann-Whitney tests.

As paper pre and post-test performances were comparable (pre-test tactile symbol recognition = 0.22 ± 0.02, post-test tactile symbol recognition = 0.23 ± 0.02, $p = 0.27$; pre-test memory spanning of sequences of tactile symbols = 2.63±0.36, post-test memory spanning of sequences of tactile symbols = 2.66±0.41, $p = 0.88$), we pooled the results over pre and post-tests.

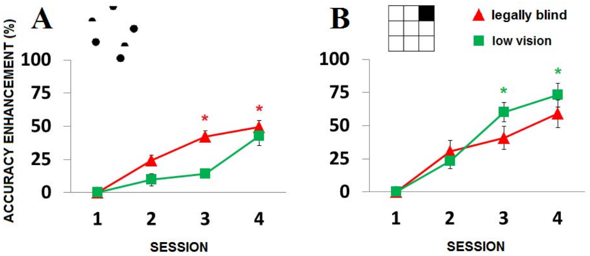

Fig. 4. Normalized accuracy enhancement (SEM indicated) across sessions in the tactile symbol recognition test (A) and in the memory spanning of sequences of tactile symbols test (B) using raised-line drawings. *Asterisks* indicate a significantly larger accuracy enhancement relative to the baseline ($^*P < 0.05$).

1) Tactile Symbol Recognition and Enumeration in Noise: Fig. 4 A shows the learning effects of blind and low vision groups in the tactile symbol recognition test. We can observe a significant performance improvement across sessions in the blind group (Friedman $\chi^2 = 11.05$; $p = 0.01$). Session 3 and 4 performance improvements (42% and 49.6%, respectively) are significantly larger than the baseline (both $p's < 0.03$). Learning effect seems weaker in the low vision group ($\chi^2 = 5.10$; p =0.16) even though the fourth session average endpoint is around 52% of improvement compared to the first session.

In this test we did not detect statistical differences in performance enhancements across groups (all p >0.05).

2) Memory Spanning of Sequences of Tactile Symbols: Fig. 4 B shows that both blind and low vision youngsters show a learning effect across sessions. This learning effect is significant in the low vision group ($\chi^2 = 11.43$; $p = 0.009$). Particularly, the enhancements of performance in the third and fourth session (60.2% and 73.1%, respectively) are significantly bigger than the baseline ($p < 0.05$). The learning effect seems weaker in the blind group ($\chi^2 = 5.14$; $p = 0.16$) but the average improvement in the fourth session compared to the baseline is nearly 60% (see Fig. 4 B).

Anyway, blind users performance was statistically indistinguishable from that of low vision participants (all $p > 0.35$).

3) Discussion: As expected, we observed a general enhancement in spatial abilities using raised-lines drawings. Both groups in the tactile symbol recognition and enumeration in noise test showed a performance improvement compared to the baseline around 50% at the end of the training. Performance enhancement seems even higher in the memory spanning of sequences of tactile symbols test. In this case, the performance improvement of the fourth session is above 70% in the low vision and about 60% in the blind group. The lack of statistical significance observed in some analyses seems to be due to the small sample sizes. Overall, these results represent a further confirmation of the effectiveness of traditional rehabilitation methods.

B. Results With Programmable Tactile Displays

As for raised-lines drawings, we tested the hypothesis that spatial abilities could significantly increase across sessions.

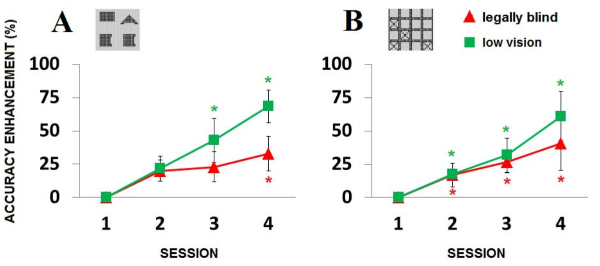

Fig. 5. Normalized accuracy enhancement (SEM indicated) across sessions in the shapes recognition test (A) and in the spatial memory test (B) using programmable tactile displays. *Asterisks* indicate a significantly larger accuracy enhancement relative to the baseline ($^{*}P < 0.05$).

We used Friedman ANOVAs and Wilcoxon matched pairs tests as post-hoc analyses. We then contrasted groups performances in all tests using Mann-Whitney tests.

1) Geometrical Shapes Recognition and Localization in Noise: Fig. 5 A shows blind and low vision groups learning effects in the shapes recognition and localization test. The learning effect in the blind group is only marginal ($\chi^2 = 6.97$; $p = 0.07$). However, the average performance enhancement in the fourth session compared to the baseline is around 33% (see Fig. 5 A) and statistically greater than 0 (Wilcoxon one-sample test; Z = 2.19; $p = 0.027$). Shapes recognition accuracy significantly improved during the training in the low vision group ($\chi^2 = 14.21$; $p = 0.002$). Recognition accuracy in session 3 and 4 (43% and 68%, respectively) is indeed significantly higher than 0 (both p's <0.04; see Fig. 5 A). We did not observe statistical differences between groups with different visual disability in the shapes recognition test. Nevertheless, as shown in Fig. 5 A, there is a clear trend towards a larger performance enhancement in the low vision compared to blind participants in the fourth session (68.3% versus 33%; $p = 0.08$).

Table II A shows testing parameters used in the first and fourth session of the shapes recognition test.

2) Memorization of Spatial Dispositions: Fig. 5 B shows blind and low vision groups learning effects in the spatial memory test. The learning effect is statistically significant in the blind group ($\chi^2 = 12.45$; $p = 0.006$).

Particularly, session 2, 3, and 4 performances (17%, 27%, and 41%, respectively) are significantly improved compared to the baseline (all p's <0.05; see Fig. 5 B). The learning effect seems even stronger in the low vision group (see Fig. 5 B). Also in this case, there is a significant performance improvement across sessions ($\chi^2 = 13.6$; $p = 0.003$). Session 2, 3, and 4 performance improvements (17.3%, 32%, and 61%, respectively) are significantly greater than 0 (all p's <0.04; see Fig. 5 B). Even though we can observe a clear trend towards increased performance enhancement in the low vision group compared to the blind group (see Fig. 5 B), from a statistical point of view there are no significant differences (all p >0.19), as it also happened with the test on geometrical shapes recognition. Table II B shows testing parameters (i.e., level of difficulty) used in the first and fourth session of the spatial memory test.

TABLE IIA

PARAMETERS USED IN THE SHAPES RECOGNITION PROGRAMMABLE TACTILE DISPLAY TEST. THE DIFFICULTY LEVELS ARE THOSE DESCRIBED IN FIG. 3

Legally Blind					Low vision				
	1st session		4th session			1st session		4th session	
Child	**Distractor difficulty**	**Time**	**Distractor difficulty**	**Time**	**Child**	**Distractor difficulty**	**Time**	**Distractor difficulty**	**Time**
01	1	25	2	15	**09**	1	25	1	25
02	3	15	3	15	**10**	2	30	2	30
03	3	20	3	20	**11**	2	25	3	15
04	3	20	3	4	**12**	2	20	2	20
05	3	20	3	10	**13**	2	25	2	20
06	2	25	2	25	**14**	3	15	3	10
07	3	15	3	15	**15**	2	25	2	25
08	3	15	3	15	**16**	3	20	3	20

TABLE IIB

PARAMETERS USED IN THE SPATIAL MEMORY PROGRAMMABLE TACTILE DISPLAY TEST

Legally Blind					Low vision				
	1st session		4th session			1st session		4th session	
Child	**Grid size**	**N° targets**	**Grid size**	**N° targets**	**Child**	**Grid size**	**N° targets**	**Grid size**	**N° targets**
01	3x3	2	3x3	2	**09**	2x2	2	2x2	2
02	4x4	3	4x4	4	**10**	3x3	4	3x3	4
03	3x3	3	3x3	4	**11**	3x3	2	3x3	3
04	3x3	4	4x4	3	**12**	2x2	2	3x3	2
05	3x3	3	3x3	3	**13**	3x3	3	4x4	3
06	2x2	2	2x2	2	**14**	4x4	3	4x4	6
07	3x3	3	3x3	3	**15**	3x3	3	3x3	4
08	3x3	3	3x3	3	**16**	3x3	3	4x4	3

3) Discussion: As it happened for raised-lines drawings tests, we observed enhancements in spatial abilities also using programmable tactile displays. In the geometrical shapes recognition test, performance improvement at the end of the training was 68% in the low vision and 33% in the blind group. Similarly, in the memorization of spatial dispositions test, the enhancement of the fourth session compared to the baseline was 61% in the low vision and 41% in the blind group.

C. Comparison Between Programmable Tactile Displays and Paper Tests

We further tested the hypothesis that programmable tactile displays could be as effective as state of the art, paper-based raised-line drawings. Therefore we compared learning effects of programmable tactile displays and paper tests using Wilcoxon matched pairs tests for each test and session. This comparison was performed only for tests that were comparable in terms of underlying involved cognitive functions (i.e., tactile symbol recognition and enumeration in noise versus geometrical shapes recognition and localization in noise on one side; memory spanning of sequences of tactile symbols versus memorization of spatial dispositions on the other side).

Overall, we could not observe any statistical difference in learning effect between programmable tactile displays and paper tests (all p's >0.16). Programmable tactile displays can be as effective as paper as a possible educational or rehabilitative tool.

Note that while results showed a similar effectiveness between traditional and technological rehabilitation methods, the latter introduces greater flexibility, personalization and it increases visually impaired users autonomy. Furthermore, when comparing tests involving symbol recognition, we note that with programmable tactile displays, low-vision participants reached significantly better performance than the baseline in the third session, and both groups significantly improved in the fourth session. With the corresponding paper tests, low-vision never reached significance, while blind participants improved the baseline in the third session. Overall, significance was therefore reached earlier when using programmable tactile displays.

In the same vein, when comparing tests involving spatial memory, we note that with programmable tactile displays both groups significantly improved already in the second session. With the corresponding paper tests, instead, low-vision participants performed better than the baseline only from the third session onwards. Thus, also with this battery of tests significance was reached earlier when using programmable tactile displays.

1) Discussion: The learning effects observed using programmable tactile displays were statistically indistinguishable from the effects observed in paper tests involving similar cognitive functions. One might argue that programmable tactile displays and raised-lines drawings we used were not completely matched in terms of required cognitive skills. For instance, the paper test involving memory spanning of sequences of tactile symbols assessed serial-spatial memory as it involved the recall of both the positions in the sequence and the order in which they were shown. On the contrary, in the corresponding programmable spatial test, several targets were presented simultaneously and so there were no temporal requirements. The reason why we prepared different tests for paper and refreshable displays was twofold. First, we wanted to limit the possibility that test order could influence the test performances. Second, we aimed at creating different tests to entertain children and to avoid their possible boredom as each of the four testing sessions lasted up to 2 h. Quite apart from these aspects, the performance similarity across testing modality is an important result, as raised-lines drawings are still the golden standard for teaching graphical concepts and rehabilitation of visually impaired children [56]. Notably, we could not observe any within-session performance difference between paper pre and post-tests indicating that the learning effects we found require time to be consolidated and they can only be observed across sessions.

Finally, the fact that youngsters improved earlier in time when using programmable tactile displays seems very encouraging, because it highlights that such displays could be thought not only as an effective (reaching significance), but also an efficient way (obtaining results earlier) to deliver rehabilitation tasks involving the development of spatial abilities of visually impaired persons.

D. Comparison Between Tests Involving Different Cognitive Functions

Then we tested the hypothesis that tests involving different cognitive functions may elicit similar improvements across sessions: to do so, we used Wilcoxon matched pairs tests for each session separately for each group.

We could not observe any statistical difference in learning effects between tests involving different cognitive functions (i.e., spatial memory and tactile shapes recognition), neither using programmable tactile displays (all p's >0.48) nor raised-line drawings (all p's >0.06).

1) Discussion: Interestingly, participants learning effects in tests involving very different cognitive functions and skills look very similar (see Figs. 4 and 5). While the shapes recognition tests required mainly a fine haptic discrimination ability, the memorization of spatial dispositions tests involved an important spatial memory load. The methodological choice to start the training with similar performance levels at the baseline might have favored a similar learning rate in different tests. In any case, these results show that very different cognitive and tactile skills can be successfully trained using both traditional and programmable display methods.

E. Self-Evaluation Report Results

We analyzed participants self-reports, specifically for the programmable tactile display tests. These were the perceived level of difficulty (PLD), perceived level of performance (PPE) and level of tiredness and their reciprocal relationships. Concerning PLD, we tested whether participants felt that the difficulty was increasing across sessions using a Friedman ANOVA for each test and group. Since we matched the level of difficulty at the beginning of the study, then increased the difficulty when participants reached ceiling effects, we hypothesized that the perceived difficulty may not increase across sessions, but could rather decrease.

1) PLD: Fig. 6 shows the self-evaluation of the level of difficulty of programmable tactile tests for each session and group. PLD did not vary across sessions and stayed at rather stable low values in both groups and tests (all p's >0.15). Overall, low vision participants were inclined to perceive the tests as more difficult than blind participants. In the shapes recognition test (see Fig. 6 A) low vision PLD is significantly higher than blind PLD in session 1 and 2 (SESSION 1: mean PLD low vision $= 5$, mean PLD blind $= 2.28$, $p = 0.045$; SESSION 2: mean PLD low vision $= 5.14$, mean PLD blind $= 2$, $p = 0.035$). In the spatial memory task (see Fig. 6 B) we can

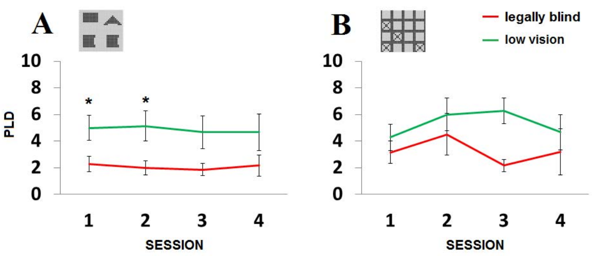

Fig. 6. Perceived Level of Difficulty (PLD) (SEM indicated) across sessions in the shapes recognition test (A) and in the spatial memory test (B) using programmable tactile displays. *Asterisks* indicate a significantly higher PLD in the low vision compared to the blind group ($*P < 0.05$).

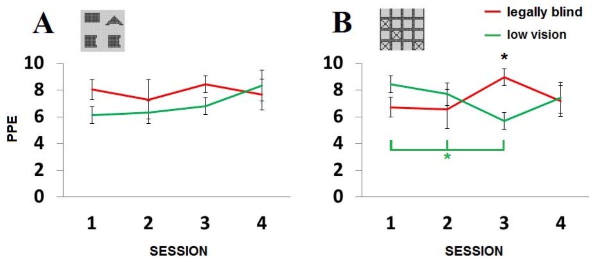

Fig. 7. Perceived Level of Performance (PPE) (SEM indicated) across sessions in the shapes recognition test (A) and in the spatial memory test (B) using programmable tactile displays. Black *asterisk* indicates a significantly higher PPE in the blind compared to the low vision group in the spatial memory test. Green *asterisk* indicates a significantly lower PPE in the third session compared to the first and second session in the low vision group in the spatial memory test ($*P < 0.05$).

observe a similar, but not statistically significant, trend (mean PLD low vision = 5.26, mean PLD blind = 3.32; $p = 0.15$).

We also checked whether there were differences in PLD across different tests. We could not observe statistical differences between spatial memory and shapes recognition test in terms of PLD (all p's >0.06). Hence, spatial memory and shapes recognition tests were perceived as similarly difficult by youngsters.

2) PPE: Fig. 7 shows the perceived level of performance (PPE) of programmable tactile tests for each session and group. Overall, PPE stayed quite stable across sessions with the exception of low vision participants PPE in the spatial memory task ($p = 0.014$). In this group, third session PPE was significantly lower compared to first and second session scores (both p's <0.02). Anyway, fourth session PPE raised up and became statistically indistinguishable from first and second session scores (both p's >0.68). Blind and low vision youngsters self-rated similarly their level of performance in both tests (all p's >0.48). Anyway, we can observe a trend towards an increased PPE in the blind group compared to the low vision group in session 3 of the spatial memory test (mean PPE blind = 8.9, mean PPE low vision = 5.7, $p = .01$; see Fig. 7 B). As for the shapes recognition test, blind participants were inclined to be more confident about their accuracy compared to low vision participants particularly in session 1 (mean PPE blind = 8, mean PPE low vision = 6.1, $p = 0.19$; see Fig. 7 A).

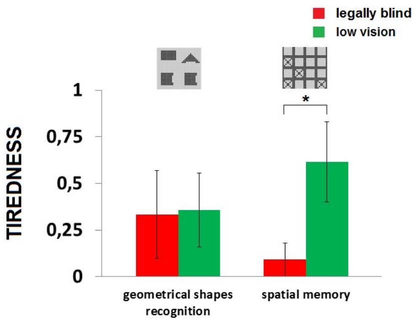

Fig. 8. Self-reported level of Tiredness (SEM indicated) after performing the shapes recognition and the spatial memory test using programmable tactile displays. *Asterisk* indicates a significantly higher level of tiredness in the low vision compared to the blind group after performing the spatial memory test ($*P < 0.05$).

Similarly, we could not find any statistical difference in PPE between spatial memory and shapes recognition test (all p's >0.07).

3) Tiredness: In order to measure the level of fatigue due to the test we subtracted the baseline level of tiredness (i.e., the 0–10 tiredness score recorded just before the test) from the level of tiredness recorded at the end of the test itself and we averaged across sessions. The reason is that we wanted to investigate the level of fatigue induced by the test *per se* regardless of the test order within the session (i.e., we counterbalanced the order of tests across sessions).

Fig. 8 shows the mean level of tiredness per test and group of youngsters.

No differences between groups emerged in the shapes recognition test ($p = 1$). On the contrary, low vision participants reported the spatial memory test as more tiring compared to blind participants ($p = 0.045$). Overall, the two tests did not differ in terms of required effort in none of two groups (both p's >0.47).

F. Relationship between age, self-evaluation reports and performance data

We investigated how the average accuracy enhancement correlates with PLD and PPE and how PPE is related to actual accuracy. Finally, we investigated the correlation between age and accuracy. To do so, we computed Spearman's rank correlation coefficients and we interpreted the strengths of the resulting scores following Evans [43].

Fig. 9 shows the relationship between PLD and averaged performance improvement in both tests and groups. As for the shapes recognition test, low vision youngsters show a moderate negative correlation between PLD and accuracy enhancement ($r_s = -0.57$; see Fig. 9 A). This correlation coefficient is also significantly different from 0 ($p < 0.002$). Blind participants show instead a weak negative correlation between those two variables in the shapes recognition test ($r_s = -0.30$; see Fig. 9 A). On the contrary, in the spatial memory test we can observe a very weak positive correlation between PLD and accuracy enhancement in low vision youngsters, whereas there is no correlation in the blind group ($r_s = 0.14$ and $r_s = -0.05$, respectively; see Fig. 9 B).

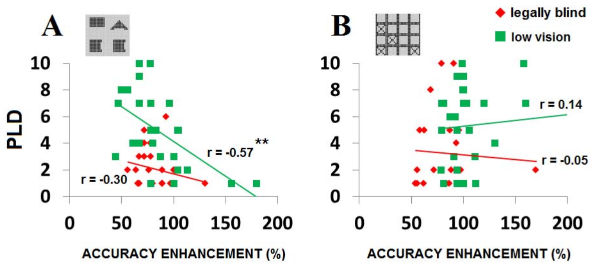

Fig. 9. Relationship between PLD and accuracy enhancement in the shapes recognition test (A) and in the spatial memory test (B) using programmable tactile displays. Spearman correlation coefficients are shown. Linear regression lines were least squares fitted. *Asterisks* indicate the correlation coefficient was significantly different from *0* ($^{**}P < 0.01$).

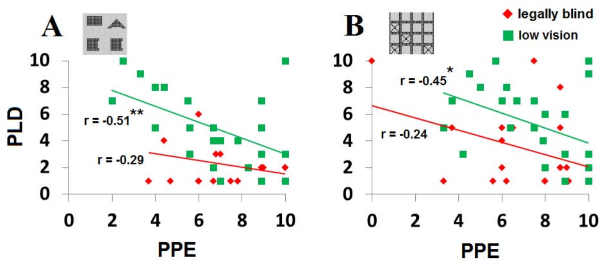

Fig. 10. Relationship between PLD and PPE in the shapes recognition test (A) and in the spatial memory test (B) using programmable tactile displays. Spearman correlation coefficients are shown. *Asterisks* indicate the correlation coefficients were significantly different from *0* ($^{*}P < 0.05$; $^{**}P < 0.01$).

As for the relationship between PPE and averaged performance improvement we only observed weak or very weak correlations. In the shapes recognition test, both groups shows a very weak positive correlation between PPE and accuracy (both $r_s < 0.18$). In the spatial memory test, low vision youngsters show a weak negative correlation ($r_s = -0.28$) whereas blind participants show a weak positive correlation ($r_s = 0.23$) between PPE and accuracy. In order to exclude artifacts related to accuracy normalization, we also analyzed the relationship between PPE and pre-normalized raw accuracies. This analysis confirms the absence of significant correlations (all p's >0.10).

Fig. 10 shows the relationship between PLD and PPE in both tests and groups. As for the shapes recognition test, we observe a moderate negative correlation between these two variables in the low vision group ($r_s = -0.51$, $p < 0.01$; see Fig. 10 A). In the blind group, the correlation is only weak ($r_s = -0.29$). PLD and PPE are similarly correlated in the spatial memory test (low vision: $r_s = -0.45$, $p < 0.05$; blind: $r_s = -0.24$; see Fig. 10 B).

Finally, we analyzed the relationship between age and accuracy enhancements. As for the spatial memory test, we could not find any correlation between those two variables in the low vision group ($r_s = -0.05$), while we observe a very weak positive correlation between age and performance enhancements in the blind group ($r_s = 0.19$). As for the shapes recognition test, the two variables were only weakly positively correlated in the low vision group ($r_s = 0.23$) and very weakly negatively correlated in the blind group ($r_s = -0.08$).

1) Discussion: As can be observed in Figs. 6 and 9, blind participants perceived the distractors test as easier compared to visually impaired youngsters. Furthermore, a measure of subjective cognitive load (PLD) is negatively correlated with performance. Since the initial (objective) difficulty levels of the distractors were high, it is possible that the game was perceived as a bit too easy by blind participants. Instead, for the low vision participants, the higher margin of improvement of both perceived difficulty (which decreased) and performance (which increased) and their negative correlation, reflects that this group was further away from ceiling effects. For this group the test appeared more engaging. Engagement in haptic-based apps designed to teach scientific content to middle school students was also recently found by Murphy and colleagues [54].

Overall, self-evaluation reports indicate that blind participants tend to underestimate both the level of difficulty and the effort required by tests, as compared to low vision youngsters. The underestimation of the perceived difficulty might explain the absence of correlation between this index and the perceived level of performance in blind participants. Furthermore, blind children and adolescents judged the spatial memory task as less tiring than low vision youngsters (Fig. 8) even though blind participants performance tended to be lower. Considering that the spatial memory task, which involved retention of several targets, was objectively more mentally demanding, low vision participants seem to provide more realistic self-evaluations than blind youngsters. In both groups, the perceived level of performance was not correlated neither with the raw accuracies, nor with the normalized performance enhancements. This highlights a general lack of correspondence between subjective and objective measures.

Collectively, these results indicate that subjective indexes may be used with caution to interpret performance of visually impaired children. In other studies with blind adults, instead, we showed that the same measure of perceived difficulty well reflected the cognitive load involved in mental mapping [10] and that it mirrored objective difficulty quite well [11], [55]. As a countermeasure, objective parameters related to performance, such as those considered in this study, seem necessary to reliably evaluate rehabilitation effectiveness. Another goal of the current study was to find out whether participant age affects learning possibility when using programmable tactile displays. As Table II shows, testing younger children certainly required to adjust the level of difficulty of tests to match their spatial abilities. Anyway, we only found weak or even negligible correlations between age and the average performance enhancement in all tests. Collectively, the lack of correlations between age and performance enhancement suggests that programmable tactile displays can be successfully used (with the proper specifications) at least as early as six years old, that is when children start to go to school.

IV. GENERAL DISCUSSION

In this work we studied the effectiveness of programmable tactile displays as a novel education and rehabilitation tool for visually impaired youngsters. The main finding of our study is that both blind and low vision participants significantly improve their spatial skills during a training when using programmable tactile displays. The final level of performance improvement compared to the first session is around 65% in the low vision and 37% in the blind groups. These performance improvements are significantly bigger than the baseline, obtained in the first of four sessions. Importantly, the improvement is apparent in two tasks requiring rather different cognitive functions and tactile skills. While the geometrical shapes recognition test required mainly a fine haptic discrimination ability, the memorization of spatial dispositions test involved an important spatial memory load. To our knowledge, this is the first evidence showing a learning effect in spatial tests using programmable tactile displays in visually impaired youngsters. Other studies showed the usefulness of haptic feedback when teaching graphical concepts to blind persons. For example Brewster [44] used a Phantom device to display line graphs in 3D. As done by Brewster, we cared about estimating the mental demand and the fatigue of blind participants. As opposed to Brewster's, our study involves participants in developmental age, it involves a longitudinal analysis, and it employs pin array displays as tactile stimulation tool. Programmable pin arrays are by construction similar to raised line drawings, a factor form to which blind children are already accustomed, therefore they may be preferred as a complementary rehabilitation tool. Giudice and colleagues [29] displayed vibrotactile geometrical shapes to blind adults, using the vibration embedded in a smartphone. This technique forces the blind person to use one finger only, therefore impairing the acquisition of graphical content with two hands (since all the fingers would feel the screen vibrating). However, the youngsters involved in our study clearly exhibited, not surprisingly, a bimanual habit toward touchable shapes: bimanual exploration leads to better performance than unimanual exploration and exploration using several fingers rather than just one seems to improve recognition of 2D raised line drawings [45], [46]. It is therefore entirely possible that part of the improvement obtained by blind persons of our study can be due to the freedom of haptically exploring with both hands static (while not vibratory) shapes.

Specifically concerning the similarity between visually impaired and blind participants, we reported in [11] a similar result when constructing cognitive maps from virtual tactile objects, although with adults only and with a completely different setup delivering minimal tactile feedback. This supports the hypothesis that when learning high-level spatial concepts, little or absence of residual vision may not be a crucial factor. Certainly, the cited works used different technological solutions and tasks compared to our study. However, the tasks are comparable at a functional level as they are all aimed at administering graphical spatial concepts in rehabilitative contexts.

Another aim of the study was to investigate possible differences between groups of children and adolescents with a different degree of visual impairment. Overall, we could not observe any statistical difference in performance between groups but a trend towards better performance in low-vision compared to blind participants in the tests with programmable tactile displays. This trend might represent actual cognitive and haptic differences between low vision and blind children. The spatial memory task we implemented requires indeed strong imagery abilities: youngsters had to retain in their spatial working memory a representation of a grid and its targets. Even though the effect of blindness on spatial memory is not entirely clear [47] and visual experience seems not to be necessary for the development of spatial complex representations [48], other studies found specific difficulties in processes such as spatial inference and spatial memory in early blind participants [2], [3], see, for reviews, [10]. These difficulties might be responsible for the slightly reduced learning effect we observed in blind children.

As for the shapes recognition test, surprisingly we observed a trend which is very similar to the one observed in the spatial memory task. However, in this case data suggest another interpretation of the difference between groups. While in the spatial memory task the lower performance of blind participants might be due to long-term impairment in spatial processing, in the shapes recognition test the baseline level of difficulty set for blind children was higher compared to low vision children, as Table II A shows. Therefore, performance improvements of the two groups might be two non- overlapping snapshots of the same learning curve. In fact, in the first two sessions low vision participants reported that their perceived level of difficulty was significantly higher compared to blind participants (see Fig. 6). This might be due to longer adaptation to non-visual tactile tasks required by persons who are not used to be blindfolded, such as our low vision sample. We recall that this sample heavily rely on residual visual capabilities in everyday life. A sighted control group would shed light on this interpretation. This would help to verify the hypothesis that the differences between groups are linked to greater exploration difficulties experienced by low-vision youngsters. In this case, we could expect that the performance of sighted participants would be the worst. However, the role of haptic exploration seems to be in agreement with some studies showing that early blind participants might be better than sighted participants in tasks such as haptic object exploration and recognition and tactile recognition of 2D angles and gratings [50], [51]. Furthermore, D'Angiulli [52] showed how blind children identified more pictures of common objects compared to blindfolded sighted children during free tactile exploration, while Brayda revealed substantially similar exploration strategies in blind as compared to sighted persons when touching virtual objects [53]. As a consequence of their superior tactile skills, in our study blind children were closer to the maximum level of difficulty imposed by the test. This might explain the reduced learning effect in this test compared to blindfolded children. As a matter of fact, this effect disappeared in the corresponding paper test (i.e., tactile symbol recognition test) in which, for the structure of the test itself, children could not reach a ceiling effect.

Future studies will extend our results with larger sample sizes, including a sighted control group, in particular to investigate more in detail the task-related differences between totally blind and low vision participants.

Importantly, the tests we proposed on programmable tactile displays were designed to *not* require the constant presence of a rehabilitation practitioner. Paper tests, instead, require so. Although during our experiments a practitioner was always available for support, participants underwent four rehabilitation sessions in a quasi-complete autonomy. The dynamic nature of the technology we adopted exploits the presentation of tactile graphics that can in principle be a priori established by the practitioner. Presenting tactile graphics with refresheable pin arrays to blind persons is confirmed to be highly relevant by recent findings and design rules [57] and by findings showing that these arrays can be used in mobility tasks for blind persons [58]. The tests required the participants to answer simple questions that can be given in full autonomy: beyond that, the evaluation of spatial abilities can potentially be done semi-automatically, or at least partially programmable tactile displays can become a tool where *spatial homeworks* can be part of rehabilitation programs, for instance in situations where the practitioner is not available. This is particularly important for tactile graphics, since spatial knowledge linked to visual conventions is probably one of the largest reasons for cultural gaps between sighted and visually impaired persons and causes social exclusion. Our study, instead, sheds new light on the development of a more autonomous way to increase spatial knowledge.

V. CONCLUSION

The main finding of this study is that both blind and low vision children and adolescents show a significant performance enhancement in spatial tasks using programmable tactile displays in a learning paradigm. The observed learning effects are comparable to traditional raised lines control tests. As for the effect of the degree of visual disability, we could not observe statistically different performances between blind and low vision youngsters but only a trend towards a better performance in the latter. In conclusion, this preliminary study indicates that visually impaired youngsters understand and can benefit from programmable tactile displays in educative and rehabilitative contexts.

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