The development of haptic processing skills from childhood to adulthood by means of two-dimensional materials.

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Abstract

Research into haptic perception has mostly focused on three-dimensional (3D) objects, and more needs to be known about the processing of two-dimensional (2D) materials (e.g. raised dots and lines and raised-line shapes, patterns and pictures). This study examines the age-related changes in various skills related to the haptic exploration of 2D raised-line and dot materials and how these skills are related to haptic picture perception. Ninety-one participants, aged 4 years to adult, were asked to perform a series of haptic tasks that entailed (1) finding dots and following lines, (2) matching elements based on texture, shape, and size, (3) matching elements based on spatial location and orientation, (4) memorizing sequences of dots and shapes and (5) identifying complete and incomplete raised-line pictures. On all the tests, the results showed that scores improved with age. Shape discrimination scores accounted for variability in comprehension scores for outline pictures. We suggested that identifying tactile pictures by touch improved with age and mainly depended on the improvement of shape discrimination skills.

Keywords: Haptic perception, Two-dimensional materials, Development

Introduction

Owing to its motor functions of grasping, transporting and transforming objects, the hand is a major tool for humans. Its numerous cutaneous receptors also provide it with a significant perceptive function. The hand is the main organ used for touch and plays a major role in gathering information about our environment. The hand is not isolated in space, but is part of a system operating the hand, namely the wrist and arm, supported by a body. Touch is a complex sense and its stimulation can either be received or sought. In light of this, two types of perception are usually defined (Gibson, 1962, 1966; Hatwell, Streri, & Gentaz, 2000, 2003): cutaneous and tactile-kinesthetic perception. Cutaneous perception (i.e., the passive sense of touch) is the result of the skin being stimulated while the part of the body in question remains stationary. This is what occurs, for example, when the wind blows against our skin, or outside pressure is applied to our body. Tactile-kinesthetic perception, or haptic perception (i.e., the active sense of touch; Revesz, 1950), on the other hand, is the result of the skin being stimulated due to exploratory movements of the hand as it comes into contact with objects.

This takes place, for example, when the hand explores a stimulus in order to feel its shape or texture. In some cases, haptic exploration is also present in passive touch situations when an outside agent (a machine or the experimenter) guides the subject's hand (see van Doorn, Dubaï, Wuillemin, Richardson, & Symmons, 2012).

The haptic system is the first sense a fetus develops (see Heller & Schiff, 1991; Heller & Gentaz, 2013). Infants and young children use it extensively to obtain information about their environment. Haptic and motor developments are closely linked: the developmental sequence of haptic perceptual abilities was shown to follow that of infants' motor development (Bushnell & Boudreau, 1991). Many studies have highlighted the efficiency of the haptic system when it comes to the identification of three-dimensional (3D) objects amongst young children (Bushnell & Baxt, 1999), school-age children (Bigelow, 1991), young adults (Bigelow, 1991) or older subjects (Ballesteros & Reales, 2004; Ballesteros, Reales, Mayas, & Heller, 2008). As far as 3D objects are concerned, haptic object processing involves the voluntary execution of a range of haptic exploratory procedures that are each able to provide information on specific properties of objects (e.g., lateral motion for texture and contour-following for precise shape; see Klatzky & Lederman, 1993; Lederman & Klatzky, 1987). Although young children can produce adult-like exploratory procedures (Kalagher & Jones, 2011; Klatzky, Lederman, & Mankinnen, 2005; Withagen, Kappers, Vervloed, Knoors & Verhoeven, 2013), the development of object recognition improves in childhood, including during mid-childhood years (8 - 12) (Morrongiello et al., 1994; Gori et al., 2008; Rentschler et al., 2004). The haptic system can also be used to process two-dimensional (2D) objects made of raised-line and dot materials, such as raised-line geometric shapes (e.g., Bailes & Lambert, 1986; Picard, Lebaz, Jouffrais, & Monnier, 2010), tactile maps (e.g., Morash, Connell Pensky, & Miele, 2013), tactile diagrams and graphs (e.g., Lederman & Campbell, 1983) and raised-line pictures of common objects (e.g., Magee & Kennedy, 1980; Lederman, Klatzky, Chataway, & Summers, 1990; Wijntjes, van Lienen, Verstijnen, & Kappers, 2008).

Research into haptic perception has mostly focused on 3D objects and more needs to be known about the processing of 2D materials. To date, compared to 3D haptic object recognition, not much research has been conducted on the development of raised-shape haptic processing abilities in childhood and adolescence. Based on the theoretical background established by Kennedy (1993) on picture perception via sight and touch, a noticeable body of work has studied the identification of tactile pictures of objects that are familiar to children (e.g., D’Angiulli, Kennedy, & Heller, 1998; Picard, Albaret, & Mazella, 2013, 2014) and adults (for literature reviews, see Heller, 2002; Heller, McCarthy, & Clark, 2005; Picard & Lebaz, 2012), but these studies do not necessarily contain a developmental dimension. D'Angiulli et al. (1998) demonstrated that sighted children aged 8 to 13 years working blindfolded only identified 9% of the tactile pictures given to them. A second group of children identified 35% of the pictures under conditions where exploration was guided by the experimenter. The authors concluded that guided exploration could help sighted children recognize tactile pictures. These results confirm the importance of exploratory movements for identifying tactile pictures. Picard et al. (2013) showed that children aged 9 to 10 years identified 37.5% of the selected images when the semantic category of the object was provided before giving the stimulus (see Heller, Calcaterra, Burson, & Tyler, 1996). Interestingly, the rate of identification for the tactile pictures increased with age, going from 32.75% for sighted children aged 5 to 7 years, to 69.25% for adolescents aged 13 to 17 years and 86.5% for young adults aged 20 to 25 years. The authors suggest that improvements in identifying tactile pictures are aided by improvements in short-term memory (Lederman, Klatzky, Chataway, & Summers, 1990; Loomis, Klatzky, & Lederman, 1991; Ballesteros, Bardisa, Millar, & Reales, 2005; Picard & Monnier, 2009).

We designed the present study to examine (i) the age-related changes in various skills related to the haptic exploration of 2D raised-line and dot materials and (ii) their relation to haptic picture perception. Firstly, this research is focused on tracing the normal development of haptic skills with respect to processing 2D stimuli. This is an important issue because, as highlighted above, compared to 3D haptic object recognition, we lack basic knowledge on haptic development with respect to 2D objects. As stated by Gori et al. (2012), research on haptic development (or the ability to extract 3D or 2D object features through exploratory actions of the hands) is important considering that haptic development is a complex developmental process of motor development that affects perceptual development. As such, our study will fill a void in the existing research on the development of a subject’s ability to haptically process 2D materials, from childhood to adulthood.

Our participants were sighted and ranged from 4 years of age to adult. Our tasks included: (1) finding dots and following lines, (2) matching elements based on texture, shape, and size, (3) matching elements based on spatial location and orientation, (4) memorizing series of dots and shapes and (5) identifying complete and incomplete raised-line pictures. They were selected so as to cover a wide variety of possible subject interactions with 2D raised-dot, line or shape materials. Based on previous findings on haptic acuity in object recognition (Gori et al., 2008) and curvature perception (Gori et al., 2012), we hypothesized that 2D haptic skills will only reach adult level at the end of childhood (10 years) or even in early adolescence (12 years).

Secondly, we looked at how scores on 2D raised-line and dot materials related to haptic outline-picture perception. Identifying raised-line pictures can indeed be improved by short-term memory improvement (Picard et al., 2013). However, regression analysis allowed us to ascertain whether our outline picture-perception scores were closely related to scanning skills (as in tasks finding dots and following lines), tactile discrimination skills (matching textures, shapes and sizes), spatial processing skills (in spatial orientation and location tasks) and short-term memory (for sequences of dots and shapes).

Method

Participants

Ninety-one French participants (45 boys and 46 girls) took part in the study. Participants were Caucasian (n = 89) and Arabic (n = 2) and came from middle- to upper-class families. They were divided into seven age groups: 4 years (n = 13: 7 boys and 6 girls; mean age = 4 years and 6 months, SD = 3), 6 years (n = 13: 5 boys and 8 girls; mean age = 6 years and 2 months, SD = 7 months), 8 years (n = 13: 8 boys and 5 girls; mean age = 7 years and 8 months, SD = 5 months), 10 years (n = 13: 7 boys and 6 girls; mean age = 10 years and 2 months, SD = 6 months), 12 years (n = 13: 6 boys and 7 girls; mean age = 12 years and 7 months, SD = 16 months), 16 years (n = 13: 6 boys and 7 girls; mean age = 16 years and 5 months, SD = 13 months), and adults (n = 13: 6 men and 7 women; mean age = 23 years and 6 months, SD = 22 months). These different age groups were selected so as to cover the different educational stages of the French education system. Therefore, children in the age 4 group were in kindergarten, while children in the groups for ages 6, 8 and 10 were in primary school. Preadolescents in the age 12 group were in secondary school and adolescents in the age 16 group were in high school. Finally, a control group of young adults was tested (University students).

Participants did not suffer from any known psychomotor deficits, intellectual deficiencies or active touch disorders. Their vision was normal or corrected to normal. The participants' manual preference was assessed using two items taken from the Edinburgh Handedness Questionnaire (Oldfield, 1971), namely the hand used for drawing and the hand used for throwing a ball. Out of the sample, ten participants (11%) had a left-hand preference (i.e., all of them answered both drawing and throwing a ball with the left hand). The others had a right-hand preference (i.e., all of them answered both drawing and throwing a ball with the right hand). None of them had used raised-line pictures prior to the research. Written consent was obtained from all the participants (or from the parents of children below the age of 10) in the present study, which was carried out in accordance with the Declaration of Helsinki, seventh revision, 2013.

Materials and Tasks

The materials included raised stimuli (dots, lines, shapes, patterns and pictures) printed on swell paper (21 x 29.7 cm, landscape format), wooden apparatus with an opaque curtain and a stopwatch. The wooden apparatus was used to enable participants to put their hand under the curtain in order to explore the stimuli via active touch, while preventing them from seeing the raised materials. There were 11 tasks, briefly described below. Due to space limitation, the complete description of each task, together with the specific raised stimuli used in each task, is provided in the Supplementary Material section.

Finding dots and following lines. These tasks assessed the participants' ability to scan a raised-dot display completely and a raised line without losing contact, respectively (see examples in Figure 1).

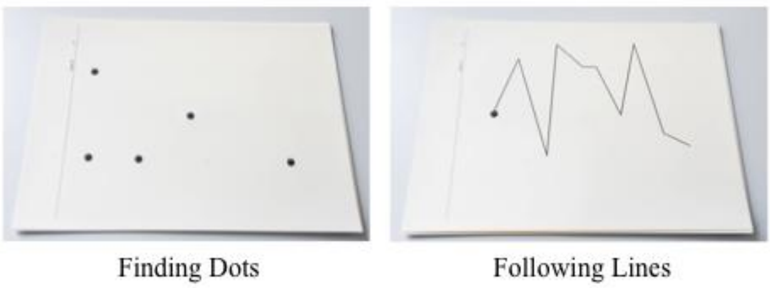

Figure 1. Examples of some of the materials used in tasks requiring finding dots and following lines.

Matching elements based on texture, shape, and size. These tasks assessed the participants' ability to match raised-line elements based on their texture, shape and size properties, respectively (see examples in Figure 2). .

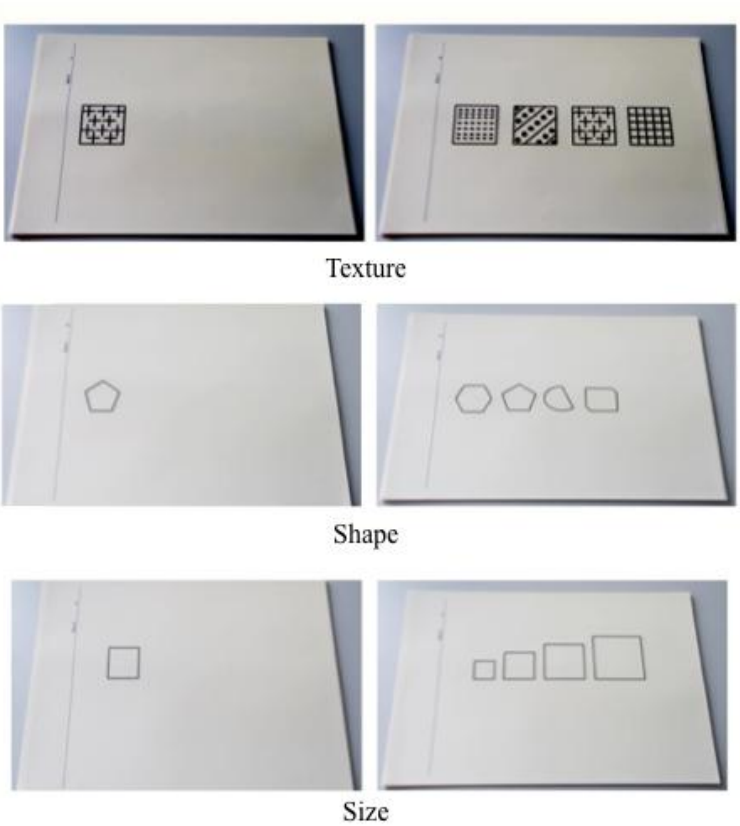

Figure 2. Examples of some of the materials used in tasks requiring matching elements of texture, shape and size.

Matching elements based on spatial location and orientation. These tasks assessed the participants' ability to match raised figures on the basis of the spatial orientation of their constituent segments and the spatial location of their internal elements, respectively (see examples in Figure 3).

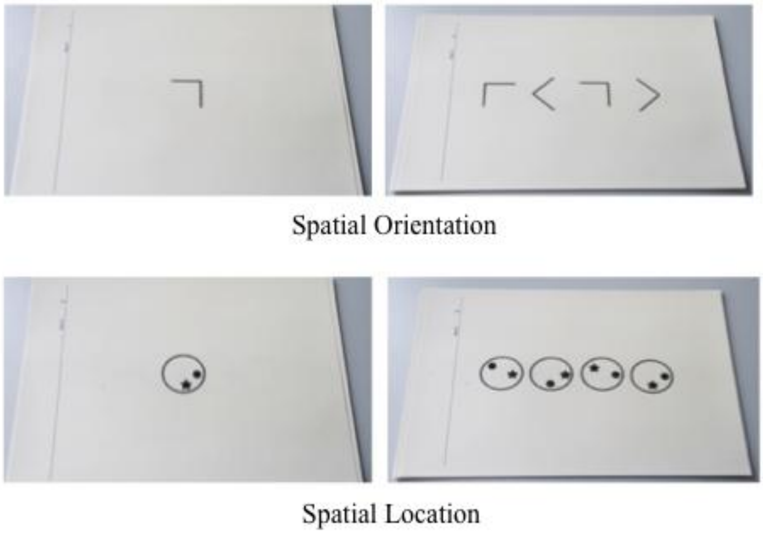

Figure 3. Examples of some of the materials used in tasks requiring matching elements on spatial orientation and location.

Memorizing series of dots and shapes. These tasks assessed the participants' ability to memorize and recall (in order) a series of raised-dot and raised-line geometric shapes, respectively (see examples in Figure 4).

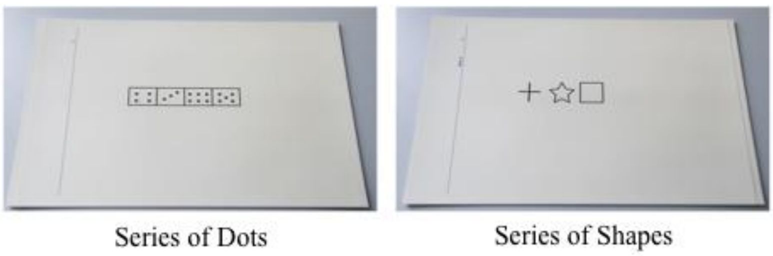

Figure 4. Examples of some of the materials used in tasks requiring memorizing series of dots and series of shapes.

Identifying complete and incomplete raised-line pictures. These tasks assessed the participants' ability to identify complete and incomplete raised-line pictures of common objects, respectively (see examples in Figure 5).

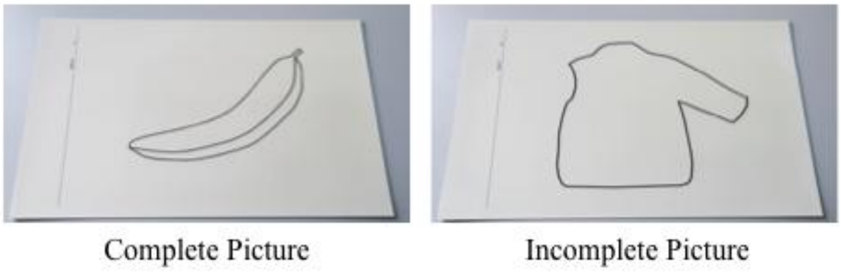

Figure 5. Examples of some of the materials used in tasks requiring identifying complete and incomplete raised-line pictures.

The maximum score for each task was 12 points. The number of items per test was six (finding dots and following lines, matching elements based on texture, shape, and size, and matching elements based on spatial location and orientation), eight (identifying complete and incomplete raised-line pictures) or twelve (memorizing series of dots and shapes). To facilitate between-score comparison, we decided to keep the maximum score for each test constant at 12 points. We therefore awarded two points per correct answer for tests with six items, one and a half points for tests with eight items and one point per answer for tests with twelve items. It should be noted that the tasks were sometimes completed successfully with strategies other than the ones expected by the authors (e.g., in the first task all the dots could be found without necessarily scanning the sheet from right to left).

Procedure

A female psychologist performed the assessments. The participants in the 4 to 10 year age group were observed at school, and those in the 12 to 16 year age group and adults were observed at home. All participants were tested individually in a quiet room and were comfortably seated at a table. Participants were given all five task categories (eleven haptic tasks) with five-minute breaks between two successive task categories. The order of presentation for the five task categories was counterbalanced across participants of each age group as per a Latin square technique. Within a category, the order of presentation for the tasks was also mixed across subjects. On average, the full session (personal information plus haptic tasks) lasted 90 minutes per participant. However, the duration of the testing period varied greatly depending on the participant's age, alertness and level of motivation. For children, the examination was often divided into two sessions. At the end of the testing time and/or during the breaks, the experimenter rewarded the participants with candies and chocolates, in addition to warm encouragements for their participation in the test.

Data Analysis

Participants were assigned a score for each of the eleven haptic tasks (range = 0-12 points), as well as a composite score, which corresponded to the sum of the scores obtained for each task (range = 0-132 points). Data analysis was performed using SPSS. The alpha level was set up at .05 throughout the analyses.

Preliminary analyses were conducted to assess the normality of data distribution and the internal consistency of test items within each haptic task. The assumption of normality was established using Shapiro-Wilk tests and boxplots. Shapiro-Wilk tests indicated that data distribution for the composite scores for each age group did not deviate significantly from normality (all ps > .080). There were no outliers in the distribution. The reliability of the test items was determined by calculating Cronbach's alpha coefficient for each task. The internal consistency for each haptic task was satisfactory (the reliability coefficients ranged from .66 to .86).

The data was then analyzed using parametric tests. To ascertain the effect of chronological age on performance, a series of Pearson's product-moment correlation analyses were conducted between age in months and haptic scores. In addition, a series of one-way analyses of variance (ANOVAs) were conducted along with Age group (7) as a between-participant factor on the composite score, as well as on the score obtained at each separate haptic task. When significant, age effects were further analyzed using post-hoc HSD Tukey comparison tests. The sex factor was initially taken into account in the models. Because no significant differences between boys and girls were detected in the composite or task scores, the factor was not further investigated in the analysis. Finally, multiple regression analysis was conducted to test which haptic skills best predicted scores obtained for the picture tasks.

Results

Correlation analysis

Figure 6 illustrates the relationship between chronological age in months and individual composite scores. Table 1 shows the correlation coefficients (Pearson's r) obtained for age in months with respect to scores obtained at each haptic task.

Figure 6 depicts a clear and linear improvement of the composite scores (maximum value = 132 points) with increasing chronological age: whereas the youngest children obtained rather low composite scores (< 20 points), the composite scores gradually increased until they reached very high values in young adults (>120). In more detail, mean composite scores were 16.9 at age 4 (or 12.8% success in the tasks), 49.4 at age 6 (or a 37.4% success rate), 55.2 at age 8 (or a 41.8% success rate), 65.4 at age 10 (or a 49.5% success rate), 85.1 at age 12 (or a 64.4% success rate), 99.8 at age 16 (or a 75.6% success rate) and 118.9 in adults (or a 90% success rate). It should be noted that none of the participants obtained floor or ceiling composite scores. The correlation between age and composite score was high and significant: r = .92, $p < .05$ (n = 91, CI level .95 = .88 to .95). Age was a significant predictor for changes in composite score (R^2 = .85, $p < .05$).

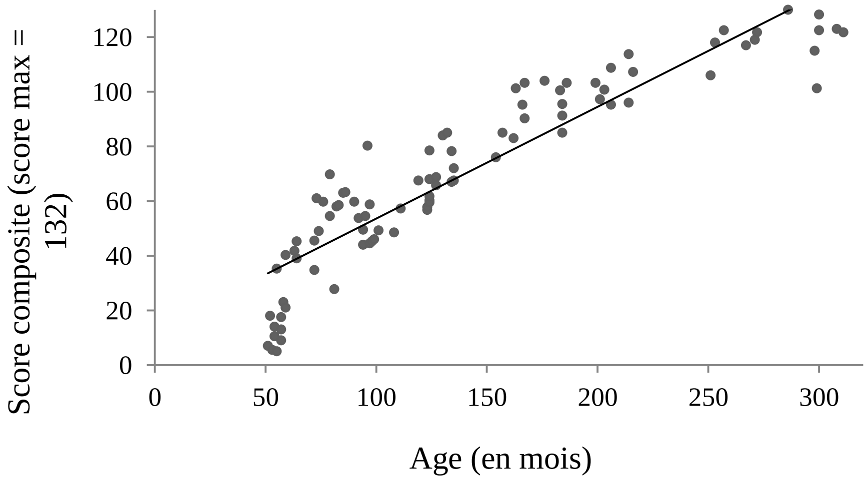

Figure 6. Correlation between age in months and composite score.

Table 1. Correlation coefficients obtained between chronological age in months and individual scores at each haptic task. Confidence Intervals (CI) are provided (level = .95).

Haptic Task	**Pearson's r (with n = 91)**	
"Scanning" tasks:		
Finding dots	.59 (CI = .44 to .71)	F (1, 90) = 46.57, p < .05
Following lines	.60 (CI = .45 to .72)	F (1, 90) = 48.95, p < .05
"Discrimination" tasks:		
Matching elements on texture	.64 (CI = .50 to .75)	F (1, 90) = 62.13, p < .05
Matching elements on shape	.83 (CI = .75 to .88)	F (1, 90) = 203.99, p < .05
Matching elements on size	.72 (CI = .60 to .81)	F (1, 90) = 98.53, p < .05
"Spatial comprehension" tasks:		
Matching elements on spatial orientation	.69 (CI = .56 to .78)	F (1, 90) = 81.54, p < .05
Matching elements on spatial location	.75 (CI = .64 to .83)	F (1, 90) = 115.53, p < .05

"Short-term memory" tasks:		
Memorizing series of dots	.89 (CI = .84 to .93)	F (1, 90) = 328.25, p < .05
Memorizing series of shapes	.89 (CI = .84 to .93)	F (1, 90) = 349.10, p < .05
"Picture comprehension" tasks:		
Identifying complete pictures	.76 (CI = .66 to .83)	F (1, 90) = 119.60, p < .05
Identifying incomplete pictures	.79 (CI = .70 to .86)	F (1, 90) = 147.73, p < .05

As can be seen in Table 1, all scores significantly correlated with age (all *ps* < .05). The correlation coefficients ranged from .59 (finding dots) to .89 (memorizing series of dots/shapes). More specifically, the skills closely related to age were short-term memory (r =.89), the ability to discriminate shapes (r = .83) and the ability to identify pictures, either incomplete (r = .79) or complete (r = .76). In contrast, the skills that were the least age-related were the abilities to find raised dots (r = .59) and to follow raised lines (r = .60).

In addition, there were moderate but significant partial correlations (controlled for age) between scores obtained for the haptic tasks *within categories*: finding dots and following lines (r_p = .37), matching elements based on texture, shape and size (all r_p = .22), matching elements based on spatial orientation and location (r_p = .48), memorizing series of dots and shapes (r_p = .44) and identifying complete and incomplete pictures (r_p = .57)[1].

One-way ANOVAs

Figure 7 shows the developmental curves obtained for each haptic task. Overall, the results indicated a gradual increase in performance score with age. Some developmental curves were clearly linear (e.g., matching elements based on texture and memorizing series of shapes), while others exhibited a step-like shape, with periods of rapid improvement and periods of stagnation (e.g., finding dots and following lines). It should be noted that within each task category, the developmental curves exhibited rather similar shapes, except for the so-called "discrimination" tasks.

[1] Note that when the analyses were conducted with scores obtained for the haptic tasks *between categories* (e.g., scores for following lines with scores for matching elements based on spatial orientation), the resulting partial correlations were comparatively lower (all r between .02 to .30), and only 35% (17 out of 48) of them reached significance. These findings suggest that, as expected, the haptic tasks were more alike within categories than between categories, thereby preventing difficulties interpreting our regression analysis due to multicollinearity.

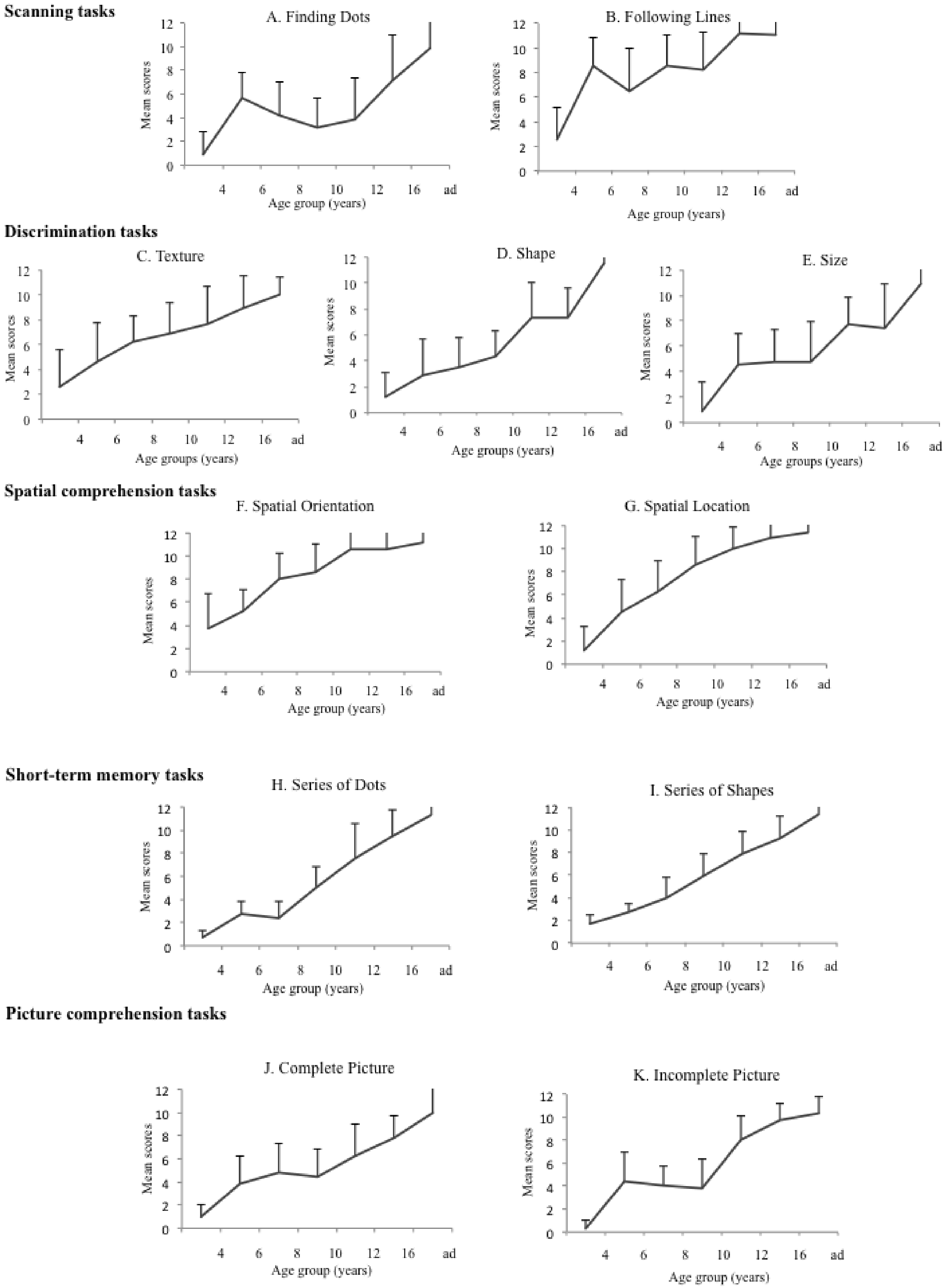

Figure 7. Mean scores obtained for each haptic task based on age group. Error bars indicate standard deviation.

As far as scanning skills are concerned, Figure 7A shows a non-linear increase in the score for finding dots based on age group. The developmental curve of these scores showed three main phases: an initial increase during early childhood (age 4 to age 6), a stagnation period from age 6 to age 10 and a final increase starting at the end of childhood (age 10) and continuing into adulthood. The ANOVA revealed a significant main effect of age on scores at the finding-dots task, $F(6, 90) = 13.56$, $p < .05$, with a large effect size, $\eta_p^2 = .49$. Tukey's HSD post hoc tests confirmed that there were significant differences in scores between age 4 and age 6 years and between age 10 and adult (all *p*s < .05). By contrast, there were no significant differences in the scores obtained between age 6 and age 10. The developmental curve of scores for following lines (see Figure 7B) showed an initial increase during early childhood (age 4 to age 6), followed by a slow increase between age 8 and adulthood. Age had a significant impact on score for the following-lines task, $F(6, 90) = 17.54$, $p < .05$, with a large effect size, $\eta_p^2 = 0.56$. Tukey's HSD post hoc tests revealed significant differences in score between age 4 and age 6 and between age 8 and adulthood (all *p*s < .05).

The developmental curve of scores for matching elements based on texture (see Figure 7C) portrayed a linear increase from age 4 to adulthood. The ANOVA revealed a significant main effect of age on these scores, $F(6, 90) = 12.07$, $p < .05$, with a large effect size, $\eta_p^2 = .46$. Tukey's HSD post hoc tests confirmed the presence of a significant difference in texture scores between age 4 and adulthood ($p < .05$). The developmental curve of scores for matching elements based on shape (see Figure 7D) showed a gradual increase from age 4 to age 12, followed by a plateau at adolescence (up to age 16) and a subsequent increase from the end of adolescence to adulthood. Age had a significant effect on these scores, $F(6, 90) = 32.83$, $p < .05$, with a large effect size, $\eta_p^2 = .70$. Tukey's HSD post hoc tests indicated significant differences in scores between age 4 and age 12 and between age 16 and adulthood (all *p*s < .05). The developmental curve of scores for matching elements based on size (see Figure 7E) showed an initial increase during early childhood (age 4 to age 6), followed by a plateau phase between age 6 and age 10, and a subsequent increase between age 10 and adulthood. The ANOVA showed a significant main effect of age on these scores, $F(6, 90) = 19.40$, $p < .05$, with a large effect size, $\eta_p^2 = .58$. Tukey's HSD post hoc tests revealed significant differences in scores between age 4 and age 6 and between age 10 and adulthood (all *p*s < 0.05).

Scores for matching elements based on spatial orientation and location (see Figure 7F and Figure 7G) both increased linearly according to age group. Age had a significant effect on the score for spatial orientation, $F(6, 90) = 25.31$, p < .05, with a large effect size, $\eta_p^2 = .64$, and spatial location, $F(6, 90) = 39.99$, $p < .05$, with a large effect size, $\eta_p^2 = .74$. Tukey's HSD post hoc tests indicated that for both spatial tasks there was a significant difference in scores obtained by children at age 4 and adults (*p*s < .05).

The developmental curves of scores for memorizing series of dots and shapes (see Figure 7H and Figure 7I) showed a linear increase from age 4 to adulthood. The age effect was significant for both memory tasks (dot series: $F(6, 90) = 62.31$, $p < .05$, $\eta_p^2 = .82$; shape series: $F(6, 90) = 65.42$, $p < .05$, $n_p^2 = .82$). Tukey's HSD post hoc tests indicated significant differences in scores between age 4 and adulthood for both tasks (*p*s < .05).

Finally, for picture comprehension tasks, the developmental curve of scores for identifying complete pictures (see Figure 7J) showed an initial increase during early childhood (age 4 to age 8), followed by a plateau between age 8 and age 10 and a subsequent increase between age 10 and adulthood. The ANOVA indicated a significant main effect of age on these scores, $F(6, 90) = 22.21$, $p < .05$, with a large effect size, $\eta_p^2 = .61$. Tukey's HSD post hoc tests revealed significant differences between age 4 and age 8 and between age 10 and adulthood (all *p*s < .05). The developmental curve of scores for identifying incomplete pictures (see Figure 7K) also showed three main phases: an initial increase during early childhood (age 4 to age 6), a plateau phase between age 6 and age 10 and a subsequent increase between age 10 and adulthood. Age had a significant effect on these scores, $F(6, 90) = 50.09$, $p < .05$, with a large effect size, $\eta_p^2 = .78$. Tukey's HSD post hoc tests showed significant differences in scores between age 4 and age 6, as well as between age 10 and adulthood (all *p*s < .05).

Multiple regression analysis

A forward stepwise multiple regression analysis was conducted to determine the contribution of the different haptic skills in tactile picture identification. A picture identification score was calculated by totaling the scores obtained for the two picture tasks (i.e., the score for identifying complete pictures + the score for identifying incomplete pictures) and the following model was tested: score for picture identification = constant + chronological age + score for finding dots + score for following lines + score for matching elements based on texture + score for matching elements based on shape + score for matching elements based on size + score for matching elements based on spatial orientation + score for matching elements based on spatial location + score for memorizing series of dots + score for memorizing series of shapes. Table 2 shows the Beta coefficients obtained for the model tested. The resulting R-squared was high and significant: $R^2 = .73$, $F(10, 80) = 21.63$, $p < .05$. This model was relevant as it explained 73% of the variance.

Table 2. Beta coefficients obtained for each predictor variable of the model tested.

Picture Comprehension Score =	**Beta coefficients**	
Constant	-.029	p > .05, n.s.
Age in months	.008	p > .05, n.s.
Finding dots	.026	p > .05, n.s.
Following lines	.130	p > .05, n.s.
Matching elements on texture	.039	p > .05, n.s.
Matching elements on shape	.232	$t(80) = 2.26$, $p < .05$*.
Matching elements of size	.077	p > .05, n.s.
Spatial orientation	- .054	p > .05, n.s.
Spatial location	.015	p > .05, n.s.
Memorizing series of dots	-.020	p > .05, n.s.
Memorizing series of shapes	.293	$t(80) = 1,96$, $p = .053$*

Inspection of the Beta coefficients showed that only scores for matching elements based on shape proved to significantly account for the variability in the tactile picture identification scores ($\beta = .232$, $t(80) = 2.26$, $p < .05$). Scores for memorizing series of shapes only slightly contributed to the variance ($\beta = .293$, $t(80) = 1,96$, $p = .053$). None of the other Beta coefficients were significant (all *p*s > .05).

Discussion

The purpose of this research was twofold: (i) to map the normal development of 2D haptic skills amongst sighted (blindfolded) participants aged 4 to adult and (ii) to explore the relations between the haptic exploration of 2D raised-line and dot materials and haptic picture perception. Firstly, our findings indicated that the entire set of selected haptic tasks (n = 11) displayed a developmental sensitivity, with strong overall increases with age. This was true for each haptic score as well as for the composite score (sum of all 11 scores). When all haptic tasks were taken together, our results showed a clear linear improvement in the composite haptic scores between the ages of 4 and adulthood. The youngest children had very low composite scores (12.8% success) whereas the adult control group obtained very high composite scores (90% success). Interestingly, the beginning of adolescence (around age 12) was a step in the normal development of haptic skills, marked by the attainment of performance of over 50% success. Based on findings from recent literature on haptic acuity (see Gori et al., 2008, 2012), we had hypothesized that 2D haptic skills would only reach adult level at the end of childhood (10 years) or even by early adolescence (12 years). Our data indicated that composite haptic scores tended to only reach adult levels by late adolescence (75% success at age 16). However, as expected, we observed some variation in performance and developmental trends based on the type of task in question. More specifically, the linear development of haptic skills was not systematic. Our results showed that certain skills, namely short-term tactile memory, the ability to distinguish between textures and spatial comprehension skills, have a linear development between childhood and adulthood. The other skills assessed (i.e., scanning dots and lines, matching elements based on shape and size and reading tactile pictures) resulted in developmental curves with periods of rapid improvement, interspersed with periods of stagnation. It should be noted that sudden rises and plateaus might be attributed to a lack of appropriate steps in terms of item difficulty in the tasks. Consequently, with additional items in some tasks, the graphs could be smoothed out. Plateaus were mainly observed in mid childhood (6 - 10 years), but some occurred in adolescence (12 - 16 years; matching elements based on shape). The linear development of tactile short-term memory from childhood to adulthood is congruent with previous observations from developmental studies (see, e.g., Ballesteros et al., 2005; Picard & Monnier, 2009).

In short, haptic skills were greatly limited in young children and most of these skills developed significantly during childhood or/and adolescence to reach adult levels by late adolescence only. Different factors may explain this long developmental process. (a) *A slow improvement in exploratory hand movements.* Old observations by Piaget and Inhelder (1947) and by Zaporozhets (1965) revealed that, in young children, exploration remains disorganized, partial, not very active, stereotyped and unsuitable for haptic tasks. A more recent study by Vinter, Fernandes, Orlandi and Morgan (2012) examined the link between the exploratory procedures used to explore 2D tactile stimuli and the level of performance obtained by children and adolescents when asked to draw the perceived shapes. The authors found that compared to children (7 years), adolescents (11 - 12 years) used many more exploratory procedures (e.g., two-handed exploration, symmetrical movements and pinching), which positively correlated with the production of correct drawings. Using a curvature perception paradigm, Gori et al. (2012) showed that haptic precision did not reach adult level before adolescence and related this long developmental process to the presence of noisy exploratory movements in children. (b) *A slow improvement in the ability to integrate piecemeal tactile information in a comprehensible whole*. Using Navon patterns (tactile hierarchical patterns made up of small circles or squares forming a large circle or square), Puspitawati, Jebrane, and Vinter (2014) showed that young children (aged 3 - 5 years) had significant difficulty understanding the 2D stimuli because they mainly paid attention to small size units when asked to name or copy the patterns. By contrast, by the age of 11 - 12 years, participants mainly produced responses that integrated all small-size units collected such that they were able to create an image of the whole object. (c) *A slow improvement in visuospatial imagery abilities*. Different studies have shown that visuospatial imagery was largely involved in the identification of 2D materials (Sathian & Zangaladze, 2001; Lebaz, Joufrais, & Picard, 2012). From this perspective, the development of visual imagery abilities could significantly explain the improvement of haptic processing skills from childhood to adulthood. (d) *Changes in the somatosensory and visual systems*. A study by Bleyenheuft, Cols, Arnould, and Thonnard (2006) showed that preadolescence was an important step in tactile spatial resolution, and related this step to cortical maturational processes. Indeed, tactile spatial resolution is known to involve activity in both the somatosensory and visual cortical areas, as both areas encounter changes at the preadolescent period (i.e., around the age of 10 - 11 years).

Secondly, our findings indicated that some priors are required before pictorial representation becomes possible. More specifically, we found that haptic picture perception was best predicted via the ability to match elements based on raised-line shapes, meaning that the ability to distinguish geometric shapes played a major part in understanding tactile pictures. Moreover, we showed that tactile memory of shapes was partly involved. Picard et al. (2013) already noted that shape span plays a role in understanding raised-line pictures. However, our results suggest that it is not short-term memory, but rather processing the shape of the drawings, that is the best prior in understanding tactile pictures. This makes sense as pictures are composed of many subtle shapes. Consistent with our hypothesis, we observed that some skills were greatly relevant to tactile picture processing, such as the ability to identify raised line shapes, whereas others were less relevant, such as the ability to differentiate between textures or scan a dot display. It should be noted, however, that our pictures were made of raised lines only and did not contain any texture or dot. This may partly explain why shape-processing was found to be a relevant predictor for performance obtained with this type of tactile picture.

The finding that shape perception is of major importance for tactile picture recognition echoes previous conclusions by Kalia and Sinha (2011), which showed that one main difficulty for young adults when reading raised-line pictures was related to knowing the shape of the object drawn. More precisely, these authors found that picture recognition rates negatively correlated with the level of complexity of the picture, and positively correlated with the picture's degree of symmetry. When asking participants to draw the object they had just explored via touch, Kalia and Sinha (2011) observed that most of the mistakes were linked to an incorrect perception of the object's overall shape. Lederman et al. (1990) tried to report on the mechanisms (perceptual-motor and cognitive) used in the haptic perception of raised-line pictures of objects via the visual mediation model. According to the researchers, there are three main stages involved in identifying raised-line drawings of common objects: obtaining the different information available via exploration (Stage 1 - encoding), creating a mental image of what is perceived via touch (Stage 2 –mental elaboration), and identifying the mental image created, retrieving the words used to name it (Stage 3 – identifying and naming the concept). Linking this model to our results would suggest that the initial difficulty in understanding raised-line pictures occurs at the encoding phase (i.e., shape perception). As early as stage 1, top-down processes may well influence the identification of raised-line shapes. It is likely that when exploring raised line pictures, children generated hypotheses about the identity of the drawn object using both the semantic information provided by the experimenter (the object's category name; e.g., "this picture belongs to vehicles") and recognition of some shapes in the picture (e.g., round shape = a wheel? It may be a car or a bicycle?), then looked for clues to confirm their assumptions (see Picard et al., 2014).

To conclude, this study is the first piece of research to assess the development of a wide range of haptic skills involved in understanding 2D tactile material, from early childhood to adulthood. We showed that these skills greatly improve with age. Therefore, despite not being very familiar with this type of material, by the end of adolescence, participants are skilled in the haptic processing of 2D materials, while children are less capable. In addition, we demonstrated that the ability to process raised-line shapes is crucial to understanding raised-line pictures, as it was the best predictor of performance obtained in our tactile-picture identification tasks. Finally, this study also provides normative data about 2D haptic processing abilities during childhood and adolescence. This data could serve as a reference for the measurement of tactile functioning in impaired children, notably those with impaired vision, for whom understanding tactile pictures is very important. Although they are still not used widely enough, raised-line drawings and raised shapes could enhance a whole wealth of materials that visually impaired children encounter at school and at home (see, for example, Kirby & D'Angiulli, 2011). Our data suggests that a potential way to improve children's understanding of tactile pictures could be to provide extensive training on processing raised-line shapes.

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Supplementary Material

Task and Material Description

Finding dots and following lines

- *Finding dots*: this task was similar to the "efficient dot scanning" test used by Ballesteros, Bardisa, Millar, & Reales (2005). It presented participants with a series of 6 test items, with an increasing number of raised dots (2, 3, 4, 5, 6, and 15 respectively), plus an initial practice card (with a single dot). The participants had to point to each dot with the index finger of their dominant hand, so as not to omit any dots on a page or point to dots several times. The diameter of each raised dot was 0.75 cm and the raised dots were distributed non-linearly on the page. Items were presented in a booklet. Instructions were as follows: "There is a dot on this card. Find it with your fingertip and point to the dot's location with your finger". The examiner took out the practice card and then presented the following six test cards with an increasing number of dots one by one, as she said: "On this card there are more dots. Search for them and each time you find one, let me know by pointing to the dot". The examiner gave two points for each card where the participant had pointed to all the dots without errors (i.e., misses or double hits).
- *Following lines*: in this task, participants were provided with a series of 6 test items (two curvilinear lines, two rectilinear lines with right angles and two rectilinear lines with acute angles), plus an initial practice card (with a short curvilinear line). They had to follow each raised line with the index finger of their dominant hand, without losing contact with the line. Each line covered an area of approximately 8 x 11 cm on the page and each had a raised circle located on the left-hand side, which made the starting point for the line to be followed easy to detect. Items were presented in a booklet, in a set order for the test items (from curved to straight with acute angles). Instructions were as follows: "There is a line on this card, which may take several turns. A small circle indicates the start of the line. Look for the circle on the left-hand side, and then follow the line with your finger, without losing contact. You must not lift your finger until you have arrived at the end of the line". The examiner took out the practice card and then presented the six test cards one by one as she repeated the instructions. The examiner gave two points for each card where the participant had traced the whole line, without losing contact.

Matching elements based on texture, shape, and size

For each task, participants were presented with a series of 6 test items (plus an initial practice test). Items were presented in a booklet, in a set order (which was randomly determined) for the test items. For each item, participants were first presented with a single stimulus (the standard), which they had to explore and memorize using their dominant hand. They were then presented with a series of four comparison stimuli (three distractors plus the standard), which they had to explore one after the other (from left to right). For each comparison stimulus, participants had to indicate whether or not the stimulus was identical to the standard. The matching task was performed on the basis of a memorized representation of the standard, as the participants were not allowed to refer back to the standard when they explored the comparison series. Criteria for constructing the comparison series were as follows: the location of the target stimulus in the comparison series was varied across test items such that it was never located in the first position, and its location (2^{nd}, 3^{rd}, or 4^{th} position) was repeated twice for all the test items. Instructions for the three tasks were as follows (respectively): "On this card, there is a square that contains a special texture/geometric shape/shape of a specific size. Explore it with your fingers, paying careful attention to its texture/shape size and memorize it". The examiner took out the card with the standard, and presented it along with the comparison stimuli, as she said: "On this new card, there are four squares/shapes/shapes of different sizes. Explore them one by one with your fingers and tell me for each one if the texture/shape/size is the same as the one you explored on the previous card." The examiner gave two points for each correct recognition of the standard stimulus without errors (no false detection).

- *Texture*: the stimuli used were raised-line squares filled with different textures (small crosses such as +, grid lines, grid points, horizontal lines, vertical lines, thick oblique lines, small horizontal rectangles, small vertical rectangles, small letter "V" in different positions, a succession of lines and oblique points, and triangular sinusoidal lines). The textures were taken from Nolan and Morris' set of textures (Nolan & Morris, 1971; see also Lederman & Kinch, 1979). The size of each square was 4 x 4 cm.
- *Shape:* the stimuli used were complex raised-line geometric shapes (half circle, three-quarter circle, oval, parallelogram, star, equilateral triangle, square, three-quarter square, pentagon, half-moon, hexagon, isosceles triangle, trapezoid and cross). The size of each shape fell within a 3 x 3 cm area.
- *Size*: the stimuli used were basic raised-line geometric shapes (square, equilateral triangle and circle). The size of the standard shape was 2 cm, 3 cm, 4 cm, or 5 cm (line length or

diameter). The comparison shapes were ranked in increasing order of size (2, 3, 4, 5 cm). There were two test items per basic geometric shape.

Matching elements based on spatial location and orientation

In both tasks, procedures and criteria for constructing the comparison series were similar to those used and described in the haptic discrimination tasks except that items were in a set order and participants used the index finger of their dominant hand to explore the stimuli et not the whole hand. Instructions for both tasks were as follows (respectively): “On this card, there is a figure made up of one or several line(s)/one or several geometric shape(s) inside a circle. Explore it with your fingers, paying careful attention to line orientation/the location of the shape(s) within the circle”. The examiner took out the card with the standard and presented it along with the comparison stimuli, as she said: “On this new card, there are four figures made up of one or several line(s)/circles. Explore them one by one with your fingers and tell me for each one if it has the same spatial orientation/the shape(s) is(are) in the same location in the circle as the one you explored on the previous card”.

- *Spatial orientation*: the stimuli were raised-line figures made up of one, two or three rectilinear segments, with each segment having a specific orientation (horizontal, vertical, or oblique). The length of a segment was 3 cm. The practice item was a one-segment figure, whereas the test items included two items with one segment, two items with two segments and two items with three segments (presented in order of increasing complexity).
- *Spatial location*: the stimuli were raised-line figures made up of a circle (size = 4 cm in diameter) containing one, two or three small, embossed shapes (a square, a circle or a star). The practice item was a one-shape figure, whereas the test items included three items with one-shape figures, two items with two-shape figures and one item with a three-shape figure (shown in order of increasing complexity).

Memorizing series of dots and shapes

Both tasks were span tasks involving the presentation of increasing series of stimuli (from 1 to 6 stimuli), which participants explored from left to right and had to memorize. Immediately after the exploration of a series, participants had to report the name of each stimulus in order. The session started with the presentation of a practice card in which the full set of stimuli was available. This practice card ensured that participants could correctly name each stimulus. Afterwards, the test session involved presenting a one-item series and continued with series of increasing length (i.e., a two-item series up to a six-item series). There were two trials per series (therefore 12 series maximum). Criteria for constructing the series were as follows: (i) a given stimulus appeared only once in a given series, (ii) the location of a given stimulus varied across the series and (iii) the last stimulus of a series differed from the first stimulus of the next series. Items were presented in a booklet, in a set order (from one- to six-item series). The session stopped when participants failed to report two series of a similar length in order. For both tasks, participants used the fingers of their dominant hand to explore series of increasing length (1 to 6) from left to right. Instructions were as follows: "On this card, one or several domino(es)/shape(s) are aligned. Explore it/them one by one with your fingers and memorize them. Once you have finished exploring all of the dominoes/shapes, tell me the number of dots/name of the shapes in their order of appearance". The examiner gave one point per series when the participant had reported all the numbers/names of shapes in their correct order of appearance, without making errors (omission or inversion).

- *Series of dots*: the stimuli used were raised-line rectangles containing 1 to 6 raised dots. The dots inside the rectangles were arranged similarly to the faces of a die. The size of each rectangle was 2 x 2.6 cm. The diameter of each raised dot was 0.3 cm.
- *Series of shapes:* the stimuli used were raised-line geometric shapes (circle, square, equilateral triangle, star, cross and rectangle). The average size of the shapes was 2 x 2 cm.

Identifying complete and incomplete raised-line pictures

In both tasks, the participants were presented with a series of 8 test items (plus two practice tests). Items were presented in a booklet, in a set order (which was randomly determined). The participants' task was to identify the object depicted (plus its missing feature for incomplete pictures). It should be noted that according to a French data base for (visual) picture naming (Cannard, Bonthoux, Blaye, Scheuner, Schreiber, & Trinquart, 2006) children as young as five could accurately identify all the depicted objects used in the picture comprehension tasks. Pictures were outline drawings, in which each line depicted a surface edge. As outline drawings have edges that are tangible as well as visible, they are thought to make sense to congenitally totally blind as well as sighted people. They were closed shapes (meaning there were no gaps in the lines with two line endings facing each other, requiring perceptual closure), with few internal details. Pictures contained mostly 2D information and a few 3D elements (i.e., the internal line of the banana). In the incomplete raised-line picture task, each drawing showed an object that was missing a part such as a limb or sleeve compared to the standard version of the object. None were objects commonly depicted with a bite, such as an apple with a bite out of it (see the Apple logo).

- *Complete raised-line pictures:* the stimuli used were eight raised-line drawings of familiar objects (banana, apple, dog, butterfly, sock, shoe, car and bicycle). The practice stimuli used were drawings of a spoon and a table. The maximum picture size was 19 x 25 cm. The pictures were simplified versions of pictures developed by Snodgrass and Vanderwart (1980). The participants were asked to freely explore each drawing with both hands and to identify what the drawing represented, as quickly and accurately as possible. In line with the procedure used by Heller et al. (1996), the object's category name was given to the participants when they were presented with each picture ("fruit" for banana and apple, "animal" for dog and butterfly, "item of clothing" for shoe and sock and "vehicle" for car and bicycle). This option was selected because pilot tests indicated that picture identification where participants were not provided with semantic cues resulted in floor performance in children. Instructions were as follows: "On this card, there is a drawing of a familiar object. Carefully explore the picture with your hands and tell me what the drawing shows, as accurately and quickly as possible. You have up to two minutes to give me an answer. The drawing is of (category name provided)". Using a stopwatch, participants were timed from the moment they first touched a picture until the time they gave a verbal response. The examiner gave 1.5 points for each card where the participant had given the expected name (or a close synonym) for the object.

- *Incomplete raised-line pictures:* the stimuli used were eight raised-line drawings of familiar objects with a missing element (a human with a missing leg, a hand with a missing nail, a comb with missing teeth, a ladder with missing rungs, a sweater with a missing sleeve, a guitar with no strings and a clock with no hands). The practice stimuli used were a house with no door and a pig with no tail. The maximum picture size was 19 x 25 cm. Pictures contained only two-dimensional information and were simplified pictures, adapted from the image completion subtest of The Wechsler Intelligence Scale for Children (Wechsler, 2005). Instructions and procedures were similar to those used and described in the picture identification task, except that participants were also asked to identify the missing feature of the object depicted. Semantic cues about the objects were given to the participants when they were presented with each picture ("this is related to or is part of the body" for the human and hand, "this is a small object you can hold in your hand" for the comb and scissors, "this is an object used by firefighters" for the ladder, "this is an item of clothing" for the sweater, "this is a musical instrument" for the guitar and "this is an object that indicates the time" for the clock). The examiner allowed a maximum of 1.5 points for each card when the participants provided the expected name (or a close synonym) for the object (.75 points) and its missing feature (.75 points).