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The Sensitive Period for Tactile Remapping Does Not Include Early Infancy

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Visual input during development seems crucial in tactile spatial perception, given that late, but not congenitally, blind people are impaired when skin-based and tactile external representations are in conflict (when crossing the limbs). To test whether there is a sensitive period during which visual input is necessary, 14 children (age = 7.95) and a teenager (LM; age = 17.38) deprived of early vision by cataracts, and whose sight was restored during the first 5 months and at age 7, respectively, were tested. Tactile localization with arms crossed and uncrossed was measured. Children showed a crossing effect indistinguishable from a control group (*N*s = 28, age = 8.24), whereas LM showed no crossing effect (*N*s controls = 14, age = 20.78). This demonstrates a sensitive period which, critically, does not include early infancy.

To swat away a fly on our arm, we need to know not only where on the arm the fly landed but also the posture of the arm in space. Thus, the location of a touch needs to be transformed from a reference frame that is skin based to one that is defined by coordinates in external space, useful for orienting responses (Azañón & Soto-Faraco, 2008; Yamamoto & Kitazawa, 2001). This remapping of tactile coordinates is evident when skin-based and external spatial representations of touch are conflicting, leading to impaired localization performance. For instance, responding to a touch when the hands are crossed is slower and prone to localization errors (Badde, Heed, & Röder, 2016; Overvliet, Azañón, & Soto-Faraco, 2011). The most commonly used paradigm for investigating tactile spatial remapping is a bimanual temporal order judgment (TOJ) task. In this task, participants feel two touches, one on each hand, and have to judge which hand was touched first. When the hands are uncrossed, participants can correctly report the order of the two stimuli even when the temporal interval between them is small. In striking contrast, when the hands are crossed, performance deteriorates dramatically, and participants often misreport the order of touches even with quite large temporal intervals between them (Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001). This *crossed-hands deficit* has been interpreted as reflecting the automatic remapping of touch into external coordinates. Because posture is irrelevant to the task (i.e., the use of somatotopic coordinates alone is, in principle, enough to solve the task), the deficit suggests that tactile processing takes into account postural information by default, even in situations in which this is detrimental to performing the task (Azañón, Camacho, & Soto-Faraco, 2010; Kitazawa, 2002).

Tactile spatial localization, and hence, tactile remapping, can occur in the absence of vision, for instance, when locating a tactile stimulus in the dark. However, some findings have highlighted the importance of online visual information in tactile remapping (Azañón & Soto-Faraco, 2007; Cadieux & Shore, 2013) and, more striking, the effects that congenital deprivation of vision have in the formation of automatic encoding of touch in external coordinates (Röder, Föcker, Hötting, & Spence, 2008; Röder, Rösler, & Spence, 2004). For instance, congenitally blind individuals, who have never experienced visual input, are unaffected by crossing

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the hands when performing a tactile TOJ task (Collignon, Charbonneau, Lassonde, & Lepore, 2009; Röder et al., 2004). This suggests that congenitally blind individuals do not remap touch into external space by default and can instead resort to a more anatomical type of mapping when needed (Röder et al., 2008, 2004; see also Eardley & van Velzen, 2011). In contrast, people who became blind later in life perform as inaccurately as sighted people in the TOJ task, even after many years of having lost sight (Collignon, Charbonneau, Lassonde, & Lepore, 2009; Röder et al., 2004). These results suggest that availability of vision, and thus, extensive visual experience, during the first years of life might lead to the establishment of cross-modal links between touch and vision that remain thereafter even in the absence of further visual input (Collignon, Charbonneau, Lassonde, & Lepore, 2009; Röder et al., 2004). This supports the idea that vision during development is a prerequisite for the acquisition of an automatic remapping of tactile events into a visual external frame of reference. This is probably related to the finding that, in sighted participants, the crossed-hands effect is weaker when crossing the hands behind the back (Kóbor et al., 2006), where no prior visual experience might have led to the configuration of visuotactile spatial representations.

These findings are even more compelling when considered in conjunction with a recent study by Ley, Bottari, Shenoy, Kekunnaya, and Röder (2013) who tested a man (HS) born with dense bilateral cataracts, whose sight was restored at the age of 2 years. Similar to congenitally blind individuals whose sight was never restored (Röder et al., 2004), HS showed no crossing deficit in the tactile TOJ task. This supports the hypothesis of the existence of a sensitive period before the age of 2 for the acquisition of an automatic use of visual–spatial representations for the coding of tactile input.

Sensitive periods are maturational epochs during which some crucial experience will have its peak effect on development or learning (Lewis & Maurer, 2005). Studies of children born with dense bilateral cataracts suggest multiple sensitive periods during which experience influences development of vision (Lewis & Maurer, 2005) and other senses (Collignon et al., 2015; Putzar, Hötting, & Röder, 2010). For instance, individuals who had cataracts removed between 6 weeks and 3 years of age displayed impaired lip-reading abilities and a reduced audio–visual interaction compared to sighted controls (Putzar, Hötting, et al., 2010; see also Putzar, Goerendt, et al., 2010). Furthermore, brief postnatal visual deprivation between 9 and 238 days can lead to large-scale cross-modal reorganization of brain circuitry typically dedicated to vision (Collignon et al., 2015).

Studies in children provide evidence that the automatic activation of external spatial reference frames for touch is not innate. Indeed, tactile spatial remapping develops with age (Begum Ali, Cowie, & Bremner, 2014; Bremner, Mareschal, Lloyd-Fox, & Spence, 2008; Pagel, Heed, & Röder, 2009; Rigato, Begum Ali, van Velzen, & Bremner, 2014), and it is not found in babies younger than 6–10 months (Begum Ali, Spence, & Bremner, 2015; Bremner, Mareschal, et al., 2008; Rigato et al., 2014). Although infants do not appear to remap touch in the early period of infancy, it remains unknown how important visual experience during this period is to the eventual development of this automatic remapping system later in life. In this study, we explored this question, by testing the existence of a sensitive period for the development of automatic remapping of touch. We tested 14 children deprived of early visual experience by dense cataracts whose sight was restored at 15–166 days of age and a single case of a teenager (LM) whose cataracts were removed at age 7 (6.62 years). We obtained an implicit measure of tactile localization by studying the perceived temporal order of two touches, one on each hand, with crossed and uncrossed arms. If there was a sensitive period during the first few months of age, we should expect differences in the crossed-hands deficit between the cataract group and controls, with the former exhibiting a smaller deficit. The automatic recoding of touch into external space is detrimental to performance on the TOJ task when the hands are crossed. If such remapping is less automatic in the cataract group, they should thus perform better. In contrast, if the sensitive period does not include early infancy, the two groups should perform similarly.

Despite the lack of early visual experience, these children showed the crossed-hands deficit indistinguishably from a matched control group, demonstrating that visual input during the first 5 months of age is not a prerequisite for normal development of tactile remapping. To demonstrate that larger periods of visual input are necessary for an automatic use of posture in tactile localization to occur, we tested the single case of LM whose bilateral dense cataracts were removed at age 7. As in the study of Ley et al. (2013), LM showed no crossed-hands deficit. These results provide evidence of the existence of a sensitive period for the development of tactile remapping that occurs beyond the first 5 months of life.

Method

Participants

Fourteen children treated for dense bilateral congenital cataracts before the age of 5 months were tested in the facilities of the Sant Joan de Déu Children's Hospital (Barcelona, Ophthalmology Department). Data from one participant were excluded from analyses due to poor performance in the uncrossed condition (see Exclusion Criteria below). In the remaining participants, the duration of the deprivation ranged from 15 to 166 days (.50–5.53 months; *M* = 3.05 months). It was defined as the period from birth until the age of the first surgery to remove the cataracts. For one participant, surgery occurred during the 4th month, although we were unable to obtain the exact date. The mean age at test was 8.12 years (range = 5.53–11.48 years; *n* = 13, 10 males, 3 female). Mean visual acuity in the better eye at the time of testing was .32, *SD* = .15 (maximum possible value = 1; for two patients, no information about visual acuity was available). Visual impairments included nystagmus (three cases), strabismus (three cases), treated glaucoma (one case), esotropia (one case), and iridocele (one case). Children were middle-class residents of Spain (12 cases) and Italy (two cases). The 14 children (13 in the final sample) were compared to 28 normally sighted controls (24 in the final sample). For each patient, two controls matched in age and sex were tested. Only in one case, a male patient had one control that was of another sex, due to the difficulties of simultaneously matching sex and age. Handedness was not assessed to avoid unnecessary increase in children's fatigue. Note that handedness in children is usually assessed using a battery of tests that require the observation of hand choice, which would have incurred in extra testing time (e.g., Kastner-Koller, Deimann, & Bruckner, 2007). Data from four controls were excluded from analyses due to poor performance in the uncrossed condition (see Exclusion Criteria below; remaining sample: *n* = 24, *M* = 8.54 years, range = 5.25–12.68 years, 18 males, 6 females). Control participants were either recruited at the ophthalmology waiting room and tested in the same conditions as the cataract group in the facilities of Sant Joan Hospital or recruited through opportunity sampling and tested at their homes (all children were middle-class residents of Spain). Informed consent was given in writing by a parent and verbally by the child.

We also tested a left-handed teenager (LM, female, left handed by self-report, 17.38 years) who had cataracts surgically removed at the age of 6.62 years. Mean visual acuity in the better eye at the time of testing was .20. She presented nystagmus and strabismus. The late intervention was caused by the impossibility of conducting this operation in LM's country of origin in the Sahara territory (Africa). At the time of testing, LM was living in Spain and finishing her final year of high school. No general cognitive impairments were evident at the time of testing. Sex and age were matched in the control group for patient LM. Five controls were also matched in left-handedness (as assessed by the Edinburgh Inventory, *M* = −.66, *SD* = .37, where −1 is a pure left handed). We chose a sample of five as this was the size of the control group used by Ley et al. (2013). For completeness, we increased the sample to 14 subjects (a standard number for a study using the crossed-hands paradigm), matching both sex and age, but independently of handedness (i.e., the last nine controls were right handed; total control sample: *n* = 14, all female, *M* = 20.77 years, *SD* = 1.97). The experiment was approved by the ethics committee of the medical council of Sant Joan de Déu Hospital and was conducted in accordance with the Declaration of Helsinki. Data from patient LM, from the younger group of cataract patients, and from the matched controls for the younger patients were collected between June 2008 and September 2011. Data from LM control's group were collected during 2016.

Apparatus and Methods

Tactile stimuli consisted of two vibrotactile stimuli at suprathreshold intensity delivered through Oticon bone conductors (sized about 1.6 × 1 × .8 cm; Type BC 461–012, Oticon, Ltd., Milton Keynes, UK). The stimulation was controlled using DMDX (Forster & Forster, 2003) and presented for 35 ms with a frequency of 200 Hz. Each tactile stimulus was inserted inside the body of a small cuddly toy (~ 13 cm in length and ~ 4 cm wide). Both toys were identical, except for a piece of cloth placed around the neck that differed in color. A toy was held with each hand, and the hands were positioned in front of the participant at a comfortable distance, either crossed or uncrossed. The two successive stimuli were presented at 12 different stimulus onset asynchronies (SOAs), which is a standard number in TOJ crossed-hands paradigms: ±1500, ±800, ±400, ±180, ±80, ±40, with negative SOA indicating left-hand first stimuli, according to the method of constant stimuli. These values were chosen to allow for a large range of responses even in children, from totally correct (at ±1500 ms) to mostly random responses (< ±40 ms). The sound of the vibrators was masked by white noise presented via headphones.

Procedure

All participants took part in a single session. Participants were asked to sit in front of a computer screen (13 in. laptop) and hold a toy with each hand. The arms were positioned either uncrossed or crossed over the body midline in front of the participant. Participants were asked to make unspeeded judgments of which stimulus came first and move the hand holding the toy that was stimulated first. In the case of the children, they were told that they were the judge of a race between the two toys and that they should report the winner of each race. Every trial started with the appearance of a picture of Spider-Man or a tiger centrally located on the screen, followed 1 s later by the first tactile stimulus. Participants were instructed to fixate on the central figure. To keep children engaged in the task, feedback was provided with the appearance of a large “¡MUY BIEN!” (very good!) or a small cross (for incorrect responses) in the middle of the screen every time they made a response. Moreover, a system of stickers of different colors was used to give children feedback on their performance. This was used to promote the engagement of the children, and therefore, the feedback provided by the stickers did not always correspond to actual performance. Participants completed 10 blocks in total, and the posture of the arms, either crossed or uncrossed, changed every block (four participants in the cataracts groups and two in the control group completed less than 10 blocks—from 6 to 9 blocks). Initial posture was randomized across participants. Each SOA was presented 10 times in each posture. Responses from the participants were recorded by the experimenter on the keyboard. We allowed children to take several breaks to paint or play with toys, which resulted in quite a long session overall (2 hr). In the case of adults, the experiment was substantially shorter (40 min), because they preferred to take shorter breaks between blocks (typically 1–3 min).

To ensure that participants were able to perform the TOJ task, two practice tests were conducted. In the first, tactile stimuli were applied to just one hand in the uncrossed hand posture (12 trials). Participants had to move the corresponding toy or indicate verbally which toy vibrated. If the participant did not understand the task, the single-target presentation was repeated. Thereafter, participants performed 12 TOJ trials in each posture using SOAs from 735 to 1235 ms. All participants successfully completed at least one correct run of both practice tests.

Analyses

TOJ performance was quantified using probit analysis as a measure of precision (Badde, Heed, & Röder, 2014; Heed, Backhaus, & Röder, 2012; Shore et al., 2002). The mean proportions of “right-hand first” responses were first calculated for each participant, condition, and SOA. These proportions were then transformed into their standardized *z*-score equivalents and then linearly regressed onto their corresponding SOA values (in seconds) ranging from −180 to 180 ms. The regression slope was used as a measure of TOJ performance with steeper probit slopes indicating better performance. Only the shorter SOAs (−180 to 180 ms) were considered to derive the slope parameter as larger SOAs might include ceiling effects, artificially reducing the estimated slope (Badde et al., 2014; Heed et al., 2012; Ley et al., 2013; Shore et al., 2002). To corroborate our results, we also analyzed the cumulated percentage of correct responses over all SOA (i.e., accuracy; Cadieux, Barnett-Cowan, & Shore, 2010; Heed et al., 2012). This measure has the advantage of being free of the assumption that the response profile across SOA follows a specific distribution (as it is assumed by probit transformation) and includes data from all SOAs. Trials where the participant was distracted or no clear answer was given were removed from analyses (M = .48% of trials across the children groups).

LM was compared to the controls by using a two-tailed Bayesian standardized difference test (BSDT; Crawford, Garthwaite, & Porter, 2010), which compares the standardized difference of LM on the crossed and uncrossed postures against the difference between the performance in these postures in the control group. The test estimates the probability that the standardized difference for a member of the control group would be smaller than that of LM and an effect size Z-DCC (Crawford et al., 2010), calculated using the following formula:

$$Z_{DCC} = \frac{[(x-\overline{x})/s_x]-[(y-\overline{y})/s_x]}{\sqrt{2-2r_{xy}}}$$

where the case’s scores on the two tasks are converted to *z* scores based on the control means and standard deviations (r_{xy} corresponds to the correlation between the two tasks in the control sample). Thereafter, Monte Carlo iterations of this formula are performed to provide the lower and upper endpoints for a 95% credible interval for the true effect size (Crawford et al., 2010). The test was performed twice: with the control group matched in sex, age, and handedness (*n* = 5), and with the full control sample (matched only in terms of sex and age; *n* = 14).

To compare LM's results with the study of Ley et al. (2013), we also performed a modified two-tailed *t* test for comparison of a single case's score to the score obtained in a control sample (Crawford et al., 2010). A single score was obtained by subtracting crossed minus uncrossed performance. *Z* scores indicating the probability of LM falling into the distribution of the control group data were provided.

A comparison between LM and a sample of the crossed-hands deficit of 343 participants is also provided. Data were taken with permission from 12 published studies and 2 unpublished studies that tested similar bimanual TOJ paradigms with crossed and uncrossed arms (corresponding to 22 experiments). Published data (included in parentheses are the names of the experiments and conditions): first study (Yamamoto & Kitazawa, 2001; main TOJ task): *n* = 20; second study (Wada, Yamamoto, & Kitazawa, 2004; left- and right-handed groups): *n* = 32; third study (Schicke & Röder, 2006; hands-only condition): *n* = 10; fourth study (Azañón & Soto-Faraco, 2007; Experiments 1 and 2 - congruent conditions only): *n* = 39; fifth study (Roberts & Humphreys, 2008; Experiments 1 and 2): *n* = 18; sixth study (Ley et al., 2013; controls for patient HS in Experiment 1): *n* = 5; seventh study (Badde et al., 2014; Experiment 2-TOJ single task): *n* = 17; eighth study (Badde et al., 2016; TOJ task): *n* = 19; ninth study (Azañón, Stenner, Cardini, & Haggard, 2015; Experiment 1-continuous condition): *n* = 12; 10th study (Nishikawa, Shimo, Wada, Hattori, & Kitazawa, 2015; young and elderly groups, participants that were tested both in the crossed and uncrossed conditions only): *n* = 41; 11th study (Azañón, Radulova, Haggard, & Longo, 2016; Experiments 1 and 4-finger conditions): *n* = 29, 12th study (Azañón, Mihaljevic, & Longo, 2016; Experiments 1 , 2, and 3 - aligned conditions only): *n* = 48. The unpublished data correspond to data of 39 participants (from currently two unpublished studies from our laboratory) plus the 14 controls for LM in this study.

Data for the histogram were analyzed using both probit analyses and accuracy. In the case of the probit, only data from the intermediate SOAs were used (maximum SOA 110–240 ms), as larger SOAs would include ceiling effects (Badde et al., 2014; Heed et al., 2012; Ley et al., 2013; Shore et al., 2002), especially in the uncrossed posture and in studies where very long SOAs were included. Given that each study included a different range of SOAs, we chose the range for each study that could produce a maximum probit slope (if a subject was perfect) of around 22.95, which is the maximum slope that can be obtained in the present study using the intermediate SOAs of −180 ms to 180 ms. If the maximum possible slope was smaller than 22.95 by 2.5 units, two SOA values (one negative and one positive) were excluded, until the maximum possible slope was larger than 22.95. The maximum possible slope across experiments with the selected SOAs had an average of 27.95 (maximum = 44.00, minimum = 20.53; *SD* = 7.26). We used this conservative procedure to ensure that differences in the SOA range would not benefit LM results but would set her performance in the lower limit of possible slope values. Indeed, her performance with uncrossed hands was below the top 25% of the data. Importantly, regardless of the use of this conservative procedure, her performance with crossed hands was within the top 2% of the data. Data from all the SOAs were used for the accuracy analyses.

Exclusion Criteria

To exclude participants who did not understand the task and gave random responses, we compared performance when the left hand was stimulated first (negative SOAs) with performance when the right hand was stimulated first (positive SOAs) with a paired-sample *t* test for each participant in the uncrossed condition (Pagel et al., 2009). Participants were excluded from further analysis when the percentage of right-hand first responses did not differ between right- and left-hand first stimuli ($p > .1$). Five participants were excluded according to this criterion in the study with children, one child operated for cataracts and four controls. Accuracy across SOAs in the uncrossed condition was below 60% in these participants. Accuracy in the uncrossed condition for the rest of the sample was above 60% (*M* = 83%, *SD* = 9.3%). Thus, only children who had understood the task instructions and could perform the task in the uncrossed posture were included in the final sample.

Results

Cataracts Removed Before 5 Months of Age

Thirteen children treated for bilateral congenital cataracts before the age of 5 months were compared to 24 normally sighted age and sex-matched controls. As shown in Figure 1, there was a general detriment in performance when children performed the task with hands crossed compared to uncrossed. This replicates the well-known crossed-hands deficit (Shore et al., 2002; Yamamoto & Kitazawa, 2001). This was confirmed by a main effect of posture on the probit analyses in a mixed analysis of variance with posture as within-subjects factor and group as a between-subjects factor, $F(1, 35) = 34.66$, $p < .001$, $\eta_p^2 = .50$. Critically, however, there was no main effect of group, $F(1, 35) = 2.75$, $p = .11$, $\eta_p^2 = .07$, nor an interaction of group and posture, $F(1, 35) = .86$, $p = .36$, $\eta_p^2 = .02$. Similar crossed-hands deficits were observed in the cataract, M crossed-hands deficit = 5.10, $SD = 3.82$, $t(12) = 3.59$, $p = .003$, $d_z = .99$, and the control group, $M = 7.01$, $SD = 6.38$, $t(23) = 5.39$, $p < .001$, $d_z = 1.10$.

To circumvent the assumption that the response profile across SOAs follows a specific distribution, as in probit analyses, we also computed the overall accuracy (Cadieux et al., 2010). Again, only the main effect of posture was significant, $F(1, 35) = 63.23$, $p < .001$, $\eta_p^2 = .64$; interaction, $p = .25$. Furthermore, there was no correlation between the amount of crossed-hands deficit in the cataracts group and the duration of the deprivation ($r^2 = .03$, $p = .58$; excluding the participant whose exact data of surgery are unknown).

Overall, these results suggest that visual input during the first 5 months of age (3.05 months in average) is not critical for the development of an automatic external reference frame for touch.

Case Study

As for the younger group, we found a clear crossed-hands deficit in the control group, $t(13) = 10.95$, $p < .001$; $d_z = 2.93$ (Figure 2). Thus, in the uncrossed condition, slopes were steeper (M probit = 17.88, $SD = 3.68$) than in the crossed condition ($M = 6.10$, $SD = 3.85$). This pattern of results was observed in every control. In striking contrast, LM showed similar performance in both postures (uncrossed: 19.63, crossed: 17.86), showing no apparent crossed-hands deficit. The lack of a crossing effect cannot be attributed to the order in which LM performed the two conditions, as she started the task with hands crossed so any effect of practice would increase the crossed-hands deficit.

To verify this dissociation, we applied the two-tailed BSDT (Crawford et al., 2010), which compares the standardized difference of an individual's performance on two tasks (i.e., crossed, uncrossed) against the difference between those tasks in the control sample. The two-tailed p value for this test was .04, which estimates the probability that the standardized difference for a member of the control population would be smaller than that of LM. The effect size (Z-DCC) for the difference between LM and controls was −2.41 (95% credible interval = [−3.85 to −1.20]). To have a direct comparison with Ley's results (Ley et al., 2013), we also verified this dissociation using a modified two-tailed t-test procedure outlined by Crawford and Howell (1998). LM's test score (uncrossed minus crossed performance = 1.77) was statistically different to that of the control group ($M = 11.78$,

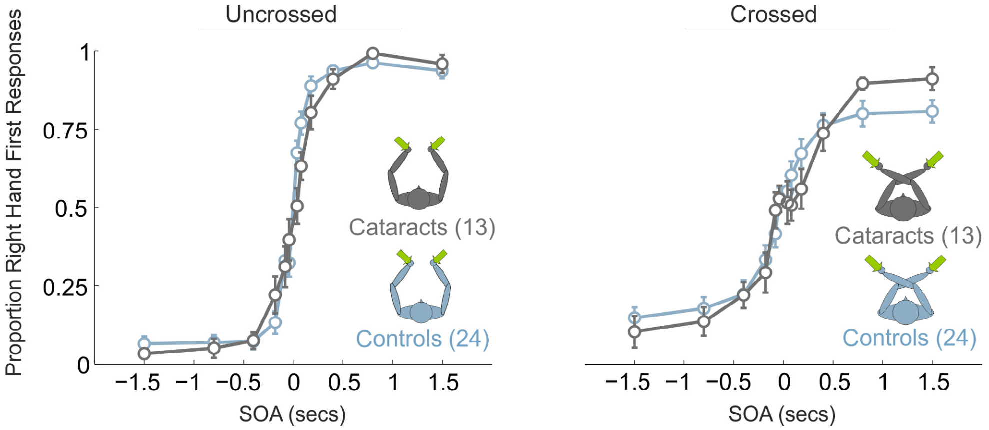

Figure 1. Proportion of right-hand first responses across the different stimulus onset asynchronies (SOAs)-Cataracts Removed Before 5 Months of Age. The graph on the left depicts data from the uncrossed conditions in the cataracts (dark gray) and the control (blue) group, respectively. The graph on the right depicts data from the crossed conditions. Error bars represent the standard error of the mean (SEM). [Color figure can be viewed at wileyonlinelibrary.com]

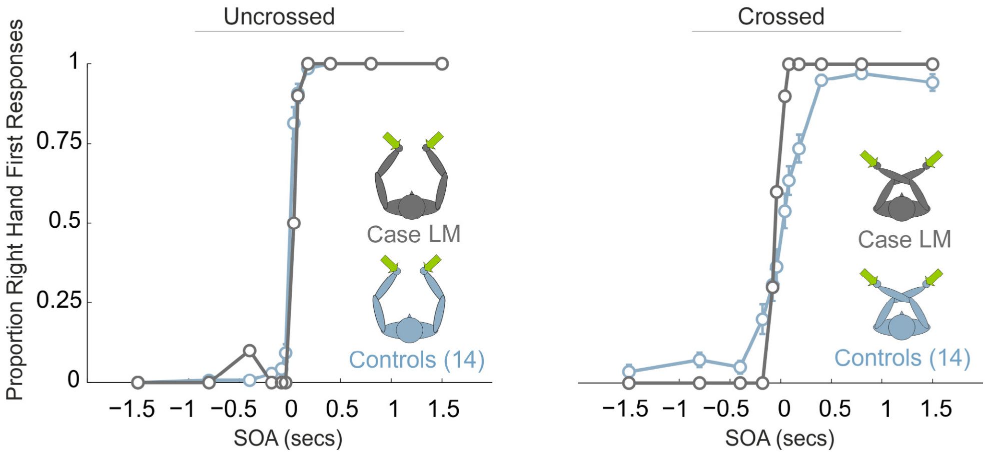

Figure 2. Proportion of right-hand first responses across the different stimulus onset asynchronies (SOAs) - case study. The graph on the left depicts data from the uncrossed conditions for LM (dark gray) and the control group (blue), respectively. The graph on the right depicts data from the crossed conditions. Error bars represent the standard error of the mean (SEM). [Color figure can be viewed at wileyonlinelibrary.com]

SD = 4.62; *t* Crawford = −2.40, *p* = .032, effect size for the difference between LM and controls = 2.49, 95% CI = [−3.55 to −1.39]).

Interestingly, similar results were obtained when comparing LM against part of her control group, matched in left handedness (as assessed by the Edinburgh Handedness Inventory; *n* = 5; *M* = −.66, *SD* = .37, where −1 is a pure left-handed). The two-tailed *p* value for the BSDT test was .02 (Z-DCC = −4.49 with a 95% credible interval = [−9.27 to −1.16]). This is relevant as some studies have reported differential effects on tactile spatial resolution with hands uncrossed, depending on handedness (Wada et al., 2004).

Similarly, analyses on accuracy revealed higher performance for the control group in the uncrossed (*M* = 96.07%, *SD* = 3.19%) than the crossed posture (*M* = 81.20%, *SD* = 5.39%), $t(13) = 11.06$, $p < .001$, $d_z = 2.96$. LM, however, showed similar values for both uncrossed (94.42%) and crossed postures (91.67%). A comparison of LM with the control group using BSDT revealed a 2% probability that the standardized difference for a member of the control population would be smaller than that of LM (*p* = .02; Z-DCC = −2.62, 95% credible interval = [−3.89 to −1.53]).

In Figure 3, we compared performance of LM in the two postures with that of 343 participants from

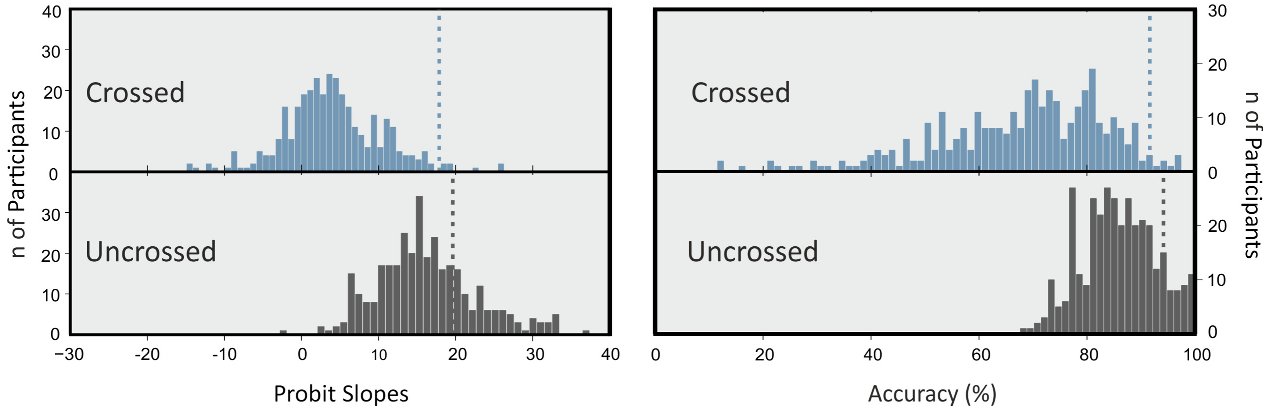

Figure 3. Histogram of the performance of 343 participants tested on bimanual temporal order judgment (TOJ) paradigms in different studies (see methods section), under crossed (blue bars) and uncrossed (dark gray bars) postures. The data consist of 12 published studies, two unpublished, and LB's control group in this study (22 experiments in total; unpublished data: 39 participants). The data are analyzed using probit analyses (left panels) and accuracy (right panels). LM's performance is marked with a dotted line. [Color figure can be viewed at wileyonlinelibrary.com]

12 published studies (Azañón et al., 2015; Azañón, Mihaljevic, et al., 2016; Azañón, Radulova, et al., 2016; Azañón & Soto-Faraco, 2007; Badde et al., 2014, 2016; Ley et al., 2013; Nishikawa et al., 2015; Roberts & Humphreys, 2008; Schicke & Röder, 2006; Wada et al., 2004; Yamamoto & Kitazawa, 2001) and two unpublished studies tested in similar bimanual crossed-hand TOJ paradigms. LM's performance in the crossed-hands posture was in the top 2–3% of the population (with a percentile of 98 and 97, for probit slopes and accuracy, respectively). Importantly, the high performance of LM in the crossed-hands posture, as compared to the rest of participants, cannot be attributed to a higher tactile temporal resolution or the fact that the task performed by LM was easier in general. This is so, as LM performed well below the top 5% when the hands were uncrossed (with a percentile of 73 and 87, for probit slopes and accuracy, respectively).

Discussion

We investigated whether the use of an automatic remapping of touch into an external reference frame requires visual input during the first months of life. Extensive previous research has shown that normally sighted humans localize touch into external coordinates automatically (Yamamoto & Kitazawa, 2001; Azañón, Camacho, & Soto-Faraco, 2010; Kitazawa, 2002). Here, we tested the spatial remapping of touch in a group of children who were born with cataracts and were, thus, deprived of vision for the first months of life (up to 5 months of age). Despite this lack of early visual experience, these children showed the crossed-hands deficit indistinguishably from a matched control group. This result demonstrates that visual input during the first 5 months of age is not a prerequisite for normal development of tactile remapping. In striking contrast, LM, whose cataracts were not removed until 6.6 years of age, showed no crossed-hands deficit at all, similar to the case recently reported by Ley et al. (2013). Together, these results demonstrate a clear sensitive period for the effects of visual exposure on tactile remapping which - critically - does not include early infancy.

Little research has tested the role of early visual input in the development of cognitive functions outside of vision. Nevertheless, it has been shown that visual input in early infancy is a prerequisite for normal development of audio–visual multisensory functions, affecting lip-reading capabilities or the McGurk illusion (Putzar, Goerendt, Lange, Rösler, & Röder, 2007; Putzar, Goerendt, et al., 2010; Putzar, Hötting et al., 2010). Critically, however, some of the participants in these studies had substantially longer periods of visual deprivation (some of them beyond infancy; from 1.5 to 3 years) than the children we tested. However, other studies have shown that shorter periods of visual deprivation (less than 6 months of age) are enough to prevent normal development of visual functions, such as holistic face processing (Grand, Mondloch, Maurer, Brent, & Columbia, 2004), visual acuity (Gelbart, Hoyt, Jastrebski, & Marg, 1982), and visual–spatial attention (Goldberg, Maurer, Lewis, & Brent, 2001).

The normal development of functions not directly related to vision may require larger amounts of experience and therefore longer periods of visual input (Wallace & Stein, 2007). Indeed, recent reports have shown that significant postnatal experience is required to remap touch automatically in external space (Begum Ali et al., 2015; Bremner, Mareschal, et al., 2008; Rigato et al., 2014). Bremner, Mareschal, et al. (2008) found that 6.5-month-olds were biased to respond to single touches on a hand in the direction appropriate to the uncrossed-hands posture, independent of whether the arms were actually uncrossed or crossed. It was not until age 10 months that manual responses were made appropriately in both postures (Bremner, Mareschal, et al., 2008). A recent study has shown even earlier signs of remapping, with 6 months infants being less accurate in their orienting responses to tactile stimuli on the feet when crossed (Begum Ali et al., 2015). The emergence of tactile remapping at this age has been proposed to be associated with the ability to perform the first reaches across the body midline, suggesting a tight relation with experience (Bremner, Holmes, & Spence, 2008; Rigato et al., 2014). In close relation, infants stare at other people's faces more than at other people's hands, and this pattern reverses gradually during the first two years of life (Fausey, Jayaraman, & Smith, 2016). Again, this change in preference might be related to a change in their own motor skills. It has also been proposed that even though children have the ability to localize touch in external space at the age of 1 year, they do not do so automatically until the age of 5.5 years (Pagel et al., 2009; Röder, Heed, & Badde, 2014). This is indeed one of the main reasons why we did not test younger children in this study. Overall, these studies highlight the role of experience in the development of an automatic remapping system (Begum Ali et al., 2014, 2015; Pagel et al., 2009; Rigato et al., 2014).

The present results show that deprivation of visual input during the first 5 months of age is not enough time to prevent the development of automatic, visually based remapping of touch. Indeed, children operated before the age of 5 months did not show any apparent difference with the controls. Note, however, that even though the first signs of tactile remapping are observed a bit later in life (after 6 months of age or later; Begum Ali et al., 2015), 5 months of visual deprivation could have been enough to affect processing of functions that emerge later in life. Indeed, early visual deprivation has shown to impact on the normal development of capabilities that will not appear until later in development (Lewis & Maurer, 2009; Maurer, Mondloch, & Lewis, 2007). For instance, visual deprivation before the first 6 months of age affects normal sensitivity to high visual–spatial frequencies (Ellemberg, Lewis, Maurer, Hong Lui, & Brent, 1999), despite the fact that deprivation ended years before visually nonimpaired children are able to see such high-spatial frequencies. Even stronger, 7 weeks of visual deprivation is enough to prevent normal development of sensitivity to fine detail (i.e., visual grating acuity) when children are older than 5 years old (Maurer & Lewis, 2001).

On the other hand, the performance of LM, whose cataracts were removed at age 7, resembled that of congenitally blind individuals (Röder et al., 2004). This suggests that the emergence of automatic remapping of touch in visually based external space requires visual input during some period of time. These findings provide confirmatory evidence of a single case of a man born with cataracts who was operated on at the age of 2 presented by Ley et al. (2013). Similar to LM and congenitally blind individuals, this participant showed no crossing effect in a tactile TOJ task, suggesting anatomical rather than visual external coding of touch. Importantly, we also showed the prevalence of the crossed-hands deficit in the sighted population, by means of a histogram depicting the performance of more than 300 participants tested in different laboratories and using slightly different paradigms. Thus, we demonstrate here that the high level of performance showed by LM is highly unusual. Overall, these data support the hypothesis of a sensitive period for the acquisition of an automatic use of visual space for the coding of tactile input.

Importantly, the lack of crossed-hands deficit in LM as compared to the congenital group is unlikely to reflect the amount of time after deprivation, as this time was similar (LM = 10.76 years; cataracts group range from 6.51 to 11.21 years). Moreover, the lack of crossed-hands deficit in LM as compared to her control group is unlikely to be explained by a larger overall tactile experience or lower visual resolution capabilities showed by LM. First, both LM and the control group performed similarly in the uncrossed-hands posture. Second, late blind individuals, who have been blind for as long as 40 years and have higher tactile acuity than sighted individuals, show similar crossing effects in tactile TOJ tasks as sighted participants (Röder et al., 2004). Thus, the current visual status does not seem to define the extent to which remapping occurs. Furthermore, the crossed-hands deficit persists after training, which ameliorates the crossed-hands deficit to some extent but does not eliminate it (Craig & Belser, 2006). Moreover, even though a few trials in the crossed posture can ameliorate the deficit in the absence of feedback, performance is reset to a lower level after each postural change (Azañón et al., 2015). Thus, the extent of tactile experience seems unlikely to define the amount of crossed-hands deficit that a person might experience.

Finally, the lack of deficit in LM as compared to her control group is unlikely to be explained by handedness. First, there is limited evidence that handedness has any meaningful effect on tactile remapping. Indeed, handedness does not appear to influence the precision (the just noticeable difference; JND) of tactile remapping when hands are crossed, but seems only to bias left–right responses at short intervals (Wada et al., 2004). Only the uncrossed condition seems to be affected. More importantly, we found LM to perform significantly better than a control group that was matched not only in sex and age but also in handedness (n = 5).

Our results clearly demonstrate that visual input during the first years of life is crucial for the acquisition of automatic remapping of touch in external, visually based reference frame. Such automatic remapping does not recover when visual input becomes available later in life. However, visual input during the first 5 months of life is not critical for the development of this external map for touch. Thus, our data demonstrate a clear sensitive period for the effects of visual exposure on tactile remapping which, critically, does not comprise early infancy.

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