Recalibrating vision-for-action requires years after sight restoration from congenital blindness

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Abstract

Being able to perform goal-directed actions requires predictive, feed-forward control, including a mapping between the visually estimated target locations and the motor commands reaching for them. When the mapping is perturbed, e.g., due to muscle fatigue or optical distortions, we are quickly able to recalibrate the sensorimotor system to update this mapping. Here we investigated whether early visual and visuomotor experience is essential for developing the ability to recalibrate. To this end, we assessed young individuals deprived from vision due to dense congenital bilateral cataracts, who were surgically treated for sight restoration only years after birth. We compared their recalibration performance to such distortion to that of age-matched sighted controls. Their recalibration performance was impaired right after surgery. This finding cannot be explained by their still lower visual acuity, since blurring vision in controls to a matching degree did not lead to comparable behavior. Nevertheless, the recalibration ability of cataract-treated participants improved with experience, matching controls’ performance after around 2 years from surgery. Thus, the lack of early visual experience affects visuomotor recalibration. However, this ability is not lost but slowly develops after sight restoration, highlighting the importance of sensorimotor experience for brain plasticity late in life.
Introduction

Most of our visually controlled actions, such as grasping objects, proficiently walking to target locations, effortlessly making use of tools or alike, are skillful and adept. Such a fast and efficient behavior is difficult to achieve relying solely on feedback control, because sensory feedback during movements is typically delayed and would require constant monitoring. Hence, to achieve such a proficiency, we predominantly rely on feedforward control. Feedforward control avoids the use of online feedback (visual and/or proprioceptive) by including accurate model predictions. For example, successfully reaching for targets based on predictive feedforward control requires a model including the mapping between the visually estimated target location and the motor commands necessary to reach for it (Wolpert et al., 2000; 2011). Acquiring such a model needs plenty of experience and thus time. As the state of our body, the range of tools we use, or the visual input constantly change, this sensorimotor mapping requires constant updating, known as recalibration (Burge et al., 2008; Redding et al., 2005; von Helmholtz, 1867). Typically, humans are able to effectively recalibrate their sensorimotor system, which is the basis for the many visuomotor skills we perform. The first signs of the ability to recalibrate emerge in the very first weeks of life and such ability keeps sharpening during childhood (Contreras-Vidal et al., 2005; Ferrel et al., 2001; Gômez-Moya et al., 2016; McDonnell & Abraham, 1979; 1981; Riddell et al., 1999).

Here we ask whether the ability to recalibrate the visuomotor system requires visual and visuomotor experience early in life to develop. To this end, we tested a group of children and adolescents who did not have pattern vision for the first years of life due to dense congenital bilateral cataract, and therefore had no chance to perform coordinated visually-controlled actions in a skillful fashion. We investigated whether they would show the ability to recalibrate their visuomotor system immediately after the recovery of pattern vision following cataract removal surgery and, if not, whether such an ability could still be acquired with experience in the months to years after surgery.

To study the development of the ability to recalibrate, we experimentally introduced perturbations to the visual input using prism goggles that shifted the visual field laterally. The recalibration performance was then assessed using a rapid pointing task. Usually, when typically sighted adults are exposed to such visual shifts, they initially show a deviation in
their pointing movements in the same direction as the visual perturbation (systematic error) (e.g., Burge et al., 2008; Redding et al., 2005). However, this systematic error is quickly reduced by gradually updating the pointing behavior. That is, after only a few pointing movements while wearing such prisms, sighted individuals are able to correctly point to the target location again, indicating that they are recalibrated. Further, a signature of sensorimotor recalibration is the occurrence of an aftereffect upon removal of the prism distortion, i.e., a systematic displacement of the pointing movement in the opposite direction to the visual distortion. Here we tested whether cataract-treated individuals are able to recalibrate their visuomotor system, and found that it takes them several years and plenty of experience to reach a performance level comparable to that of sighted individuals.

**Results**

Participants were asked to perform a pointing task consisting of three phases (cf. Fortis et al, 2010, Frassinetti et al., 2002). First, we determined baseline performance (pre-prism phase): to this end, individuals were asked to repeatedly point toward a visual target while wearing neutral goggles that did not introduce any visual distortion. The pointing movements were performed in the absence of any visual feedback of the arm, which was occluded by the experimental setup (see Materials and Methods). Next, in the prism phase, participants executed the task while wearing prism goggles shifting the apparent target location visually by 20 prism diopters (11.31°) to the right. In this phase participants could see the tip of their index finger at the end of the pointing movement appearing from below the setup (terminal feedback), while the rest of the arm movement was hidden from view to prevent any online corrections during the pointing movement (Figure 1A, upper panel). This terminal feedback of the pointing error is generally sufficient for the sighted population to recalibrate their visuomotor system from trial to trial (Burge et al., 2008; Redding et al., 2005; von Helmholtz, 1867). Finally, the distortion prisms were removed and participants were tested again with the neutral goggles in the absence of visual feedback (post-prism phase). In each trial, pointing errors were measured as the difference—in degrees of visual angle—between the target location and the pointing endpoint.
We compared the performance of a group of 20 Ethiopian children and adolescents suffering from congenital dense bilateral cataracts, surgically treated 5-19 years after birth and tested days to years after surgery, with that of two control groups (Figure 1–Table supplement 1). The first control group consisted of 20 typically developing sighted participants who were individually matched for age with the cataract-treated sample, as we found that age has an influence on the recalibration rate in the healthy population (Figure 1–figure supplement 2). In the second control group 20 sighted participants were individually matched to cataract-treated individuals for both age and visual acuity, using visual blur filters to degrade vision. This was necessary because previous research showed that measurement uncertainty in the form of visual blur can potentially result in a decreased learning rate (Burge et al., 2008). Thus, this second control group provides a baseline for the effect of visual acuity on recalibration rate. To this end, we determined the cutoff frequency of the contrast sensitivity function (CSF) in each cataract-treated participant (cf. McKyton et al., 2015; Senna et al., 2021). We then blurred vision in each control by placing a blurring filter between the participant and the visual target until the desired cutoff frequency was matched (Figure 1A, lower panel and Materials and Methods). Additionally, as prolonged visual deprivation typically results in amblyopia and in stereoacuity deficits, all participants were tested monocularly (i.e., with their dominant eye, see Materials and Methods).

We first verified whether the cataract-treated participants under normal conditions were able to point at targets. We found that they were able to point to all target locations and performed the pointing task with similar accuracy to both control groups before being exposed to the prism distortion (Kruskal–Wallis test, $\chi^2(2) = 1$, $p=0.61$, $\eta^2=0.017$ in pre-prism phase). However, despite being as accurate as controls, they were less precise (Figure 1B–figure supplement 1). Next, to quantify the recalibration rate for the different groups in the prism phase, we fitted power functions to the trial-by-trial pointing errors averaged across the participants of each group (see Material and Methods):

$$\text{Error} = a \cdot x^b$$

(1).

The parameter $a$ is the amplitude of pointing error and $b$ is the time constant, that is the recalibration rate: the larger $b$, the faster the recalibration to the visual distortion. This analysis showed that cataract-treated individuals have difficulties to recalibrate their
sensorimotor system: compared to sighted controls, the group of cataract-treated participants only marginally reduced their pointing error, although the learning was still significant (i.e., the 95% confidence interval for recalibration rate $b=-0.09$ CI=[-0.14, -0.03] did not include 0).

Instead, sighted participants tested in normal visual conditions had the fastest learning rate $b=-0.49$ (CI=[-0.54, -0.45]). As expected (4), blurring vision in sighted controls (thus matching them in CSF to the cataract patients) resulted in a reduced recalibration rate ($b=-0.27$, CI=[-0.32, -0.22]). Nonetheless, they were still much faster at recalibrating than the cataract-treated individuals (Figure 1B).

Notably, all groups showed an aftereffect: after prism removal in the post-prism phase all groups presented a pointing bias, i.e., a systematic error in the opposite direction to the displacement induced by the prism. The mean aftereffect displayed by cataract-treated participants was less pronounced than that of both control groups (around -2° vs. -4.5°, respectively; Bonferroni-corrected p≤0.0036 following Kruskal–Wallis test: $\chi^2_{(2)}=14.3$, $p=0.0008 \eta^2=0.221$; cf. Materials and Methods), and did not show an analogous trial-by-trial decay over time (Figure 1– figure supplement 1). Importantly, however, the aftereffect observed in cataract-treated participants significantly differed from zero (Wilcoxon signed-rank test, $p=0.02$), confirming the results from the prism phase that at the group level they also showed some visuomotor recalibration performance (Figure 1B).

To analyze and quantify the recalibration performance not only at the group but also on the individual level, we calculated a recalibration index ($i_{\text{recal}}$) for each participant, which summarized the performance across the entire experiment instead of analyzing each phase separately, thereby increasing power. This index allowed us to also investigate a possible development of the recalibration performance across time on an individual basis, factoring in the high variability in age and visual acuity across the tested group of cataract-treated participants. This index was calculated by taking the average between the amount of error reduction in the prism phase–Prism Recalibration–combined with the magnitude of the negative Aftereffect, normalized by the Prism Distortion ($11.31^\circ$, cf. Eqn. 2 and Eqn. 4 in Materials and Methods). Therefore, the index ranges between 0 (no recalibration) and 1 (complete recalibration):
The analysis of $i_{\text{recal}}$ agrees at the group level with the previous results of the rate parameter: it significantly differed across the three groups and, although $i_{\text{recal}}$ was substantially lower in the cataract-treated participants compared with the two control groups, it was still significantly greater than zero (Figure 1B, inset).

As the poorer performance of cataract-treated participants cannot be explained by the diminished visual acuity alone—CSF-matched controls still recalibrated significantly faster—, we also explored the contribution of time and experience that could contribute to the development of recalibration. To this end, we correlated the performance of the cataract-treated participants not only with their visual acuity, but also with the time since surgery and the age at test and at surgery. $i_{\text{recal}}$ did not correlate with age at test or with age at surgery (Figure 1D-E). This is at odds with the performance of the typically sighted population, in which we found that $i_{\text{recal}}$ increases with age and thus experience (Figure 1—figure supplement 2), and it is already greater in the youngest control children (6–7-year-old, n=11, $i_{\text{recal}}=0.62\pm0.07$) than in the whole cataract-treated sample (0.30±0.06, Wilcoxon-Mann-Whitney, p=0.03). This may well indicate that learning to recalibrate is not merely an effect of brain maturation related to age, but requires experience to develop. This is confirmed by the fact that recalibration performance is correlated with time since surgery (Pearson’s correlation coefficient, r=0.59, p=0.017). Additionally, it is also correlated with visual acuity (r=0.5, p=0.025, Figure 1C), meaning that higher visual acuity and thus a better visual input leading to better quality experience led to better recalibration performance. As learning typically follows an exponential function rather than a linear trend, we also fitted the time-since-surgery data using an exponential:

$$i_{\text{recal}} = (a - c)^{-bx} + c$$  \hspace{1cm} (3).

The asymptote $c=0.57$ was fixed to the mean performance of the CSF-matched control participants. The amplitude $a$ was fixed to 0, meaning that we assumed that without visual experience the recalibration performance corresponds to $i_{\text{recal}}=0$. From the fit we determined the time constant $b$ for the development of recalibration. This analysis subsumed all measurements obtained from the participants after surgery, including a subset of 13 individuals tested twice. Participants of this subset were tested the first time a few months
after surgery (range: 1 day-2.3 years, see Table supplement 1) and retested 4-16 months later. \( i_{\text{recal}} \) approached the asymptote, showing a performance indistinguishable from the matched controls at around 2 years after surgery (\( b=1.5, \ CI=[0.51, 2.49] \), Figure 1F).

The contribution of post-surgical experience to the development of recalibration at the individual level is also appreciable when considering the difference in recalibration performance (\( \Delta i_{\text{recal}} \)) between each CSF-matched pair of participants: control minus cataract-treated (Figure 1F, inset). The difference in performance between cataract-treated participants and their individually-matched controls tended to decrease with time since surgery, clearly highlighting the effect of experience after surgery for developing the ability to recalibrate.

The role of experience for improving the recalibration performance is further highlighted in Figure 1G, which focuses on the 13 individuals repeatedly tested. Among them, a subset of 4 participants could be even assessed right before surgery. This was possible because this small subsample presented enough residual vision to be able to point to the targets and to have their CSF measured already prior to surgery. Despite a substantial improvement of their visual acuity right after cataract removal (CSF mean±SEM pre: 2.14±0.43; post: 4.53±1), their recalibration performance did not improve accordingly, but stayed essentially the same between the pre-surgery assessment and the post-surgery evaluation occurring just a few days after surgery (\( i_{\text{recal}}=0.24±0.11 \) vs. 0.16±0.14, respectively). The thirteen cataract-treated individuals who were retested again several months after surgery showed a significantly higher \( i_{\text{recal}} \) in the second (0.41±0.07) as compared to the first post-surgical test (0.24±0.09, Wilcoxon signed-rank test, \( p=0.04, \) one-tailed). This improvement was not related to any change in visual acuity, which was comparable in the two post-surgical tests (\( \Delta \text{CSF}:1.2±0.67; t_{12}=1.35, \ p=0.2 \)).
**Figure 1. Recalibration behavior** (A) Pointing setup. Upper panel without, lower panel with blurring shield. Participants wore goggles with an eye cover over the non-dominant eye. A prism could be inserted into the goggles during the *prism* phase inducing a rightward shift. A cover was used to block vision during pointing movement. Only during the *prism* phase participants could see their terminal pointing error, by seeing the tip of their finger appearing from under the cover. Before (*pre-prism*) and after (*post-prism*) the *prism* phase, participants performed the same task without the prism and in the absence of terminal feedback. (B) Recalibration Performance. Mean pointing errors across bins of three trials from individual
participants plotted over the three phases of the experiment (prism phase in grey, error bars show SEM across participants) for the three groups: cataract-treated (red), and sighted controls tested with (light blue) and without (blue) visual blur (n=20 in each of the three groups). The dashed line represents the prismatic shift (11.31°). The inset shows the recalibration index $i_{\text{recal}}$, which summarizes the recalibration performance in prism and post-prism phases (0 no recalibration, 1 complete recalibration). The analysis on $i_{\text{recal}}$ showed that each group differed from the other (Bonferroni corrected Wilcoxon-Mann-Whitney, all $p<0.006$, following Kruskal-Wallis test, $\chi^2(2)=27$, $p=0.0001$, $\eta^2=0.38$). Although the cataract-treated group recalibrated less than the sighted control groups tested with and without visual blur ($i_{\text{recal}}$, mean±SEM = 0.30±0.06, 0.57±0.03, and 0.69±0.02, respectively), their recalibration performance was significantly greater than 0 (Wilcoxon signed-rank test, $p=0.0012$). (C) Visual Acuity. Recalibration performance $i_{\text{recal}}$ as a function of visual acuity in cataract-treated participants. Participants with higher visual acuity recalibrate more (higher $i_{\text{recal}}$, Pearson’s correlation coefficient, $r=0.5$, $p=0.025$). The data points are coloured with brighter colors indicating longer time since surgery. This shows that individuals tested soon after surgery tended to recalibrate less (smaller $i_{\text{recal}}$). Note, however, that time since surgery did not significantly correlate with visual acuity at the group level ($r=-0.03$, $p=0.8$). D) Age at surgery. Age at surgery did not significantly correlate with recalibration performance $i_{\text{recal}}$ ($r=-0.08$, $p=0.75$). E) Age at test. Age at test, similar to age at surgery, did not influence recalibration performance ($r=0.22$, $p=0.36$). F) Time since surgery. With time after surgery participants tended to exponentially improve their recalibration performance $i_{\text{recal}}$, reaching the level of the CSF-matched controls (i.e., tested with visual blur) at around 2 years from surgery. The dashed line and the light-blue shaded area indicate the mean performance and the 95% confidence intervals of the sighted CSF-matched controls, respectively. Red circles indicate the first post-surgical test. Brown circles indicate the second performance of a subset of 13 participants re-tested in the same task 4 to 16 months later, with connecting lines linking the same participant. The inset shows the difference in recalibration performance ($\Delta i_{\text{recal}}$) for each CSF-matched pair of participants: control minus cataract-treated participant as a function of the time since surgery. To capture the learning effect, these data were also...
fitted using an exponential: $\Delta \text{irecal} = a e^{-bx}$, with amplitude $a$ and time constant $b$. The difference between cataract-treated participants and their individually-matched controls tended to exponentially decrease with time since surgery with a time constant of $b=1.19\text{y}$, CI=[-.03\text{y}, 2.68\text{y}]).

G) Repeated testing of the subset of 13 participants tested over time. Four of them were tested also before surgery (since their visual acuity allowed them to see the target). Although their CSF increased due to the surgery, their pointing performance did not in the first test performed a few days after surgery. Instead, with more time after surgery (4 to 16 month) the recalibration performance of the 13 participants significantly improved (Wilcoxon signed-rank test, $p=0.04$, one-tailed).

H) Correlation between recalibration and multisensory integration (see Discussion for details). Fourteen participants took part in this and in a previous study on multisensory integration (Senna et al., 2021) at around the same time after surgery. We investigated the relationship between the performance in both tasks by correlating $\text{irecal}$ as a measure of recalibration performance and the Multisensory Influence ($\text{MI}$) as a measure of integration performance between vision and touch: $r=0.58$, $p=0.03$.

Figure 1–Table supplement 1. Clinical characteristics of the cataract-treated participants.

Figure 1–Figure supplement 1. Details on the performance in pre-prism and post-prism phases.

Figure 1–Figure supplement 2. Development of recalibration in the typically sighted population.

Discussion

Here we investigated whether individuals suffering from congenital dense bilateral cataracts, surgically treated years after birth, can develop the ability for visuomotor recalibration, which is an essential behavior enabling efficient interaction with the world. We used prism goggles to distort the visuomotor mapping and compared their recalibration performance to that of typically sighted individuals matched for age and visual acuity. Unlike typically developing individuals, who quickly recalibrated when exposed to distortions in the visuomotor mapping, we found that the recalibration ability of the cataract-treated individuals was almost absent right after surgery. Importantly, as time progressed after surgery they
improved and started to show better recalibration performance. However, it took over two years for this ability to develop to levels comparable with sighted individuals.

It seems surprising that a flexible visuomotor mapping takes so long to mature in cataract-treated individuals, since being able to quickly recalibrate the sensorimotor system is essential for everyday adept behavior. Indeed, a flexible sensorimotor system, capable of rapid modification, grants the possibility to rely on fast, feedforward motor control when interacting with the world. Healthy individuals constantly update the mapping between the visually estimated location of a target and the motor command required for reaching it. They do so for instance when using tools that artificially elongate arm length, when the body itself is altered while carrying objects, or when using glasses that induce optical distortions.

However, they also constantly refine their mapping in the presence of noise when no actual distortions occur. Despite the fact that the ability to proficiently recalibrate the visuomotor system keeps developing over the first decade of life or more to reach adult levels (Bard & Hay, 1983; Bard et al., 1990; Contreras-Vidal et al., 2005; Ferrel et al., 2001; Gómez-Moya et al., 2016; Hay, 1979; 1991), first signs of this behavior emerge very early after birth in healthy individuals. For example, a few day-old newborns are already able to direct their arm toward a visual target (von Hofsten, 1982), and infants can learn new visuomotor transformations to recalibrate the visuomotor system in response to distortions of the visual feedback within the first weeks or months of life (McDonnell & Abraham, 1979; 1981; Riddell et al., 1999). In our study with cataract-treated participants we did not find equally rapid signs of the emergence of such ability.

From a comparison between the cataract-treated individuals and the control groups we can conclude that it is neither age nor the improvement in visual acuity that is the sole determining factor for the development of the recalibration performance, but that such a development requires experience from interaction with the world. Firstly, we can determine that age is not the sole decisive factor from comparing our cataract-treated individual to the group of age-matched sighted controls, which shows that cataract-treated participants are on average much less efficient in reducing the error when exposed to a prismatic shift, and they also present less of an aftereffect following prism removal. In addition, the average rate of recalibration of the group of cataract-treated individuals, who had a mean age of 13 years, is
even slower than that of the youngest sighted controls, which was tested at 6 or 7 years of age. Furthermore, in the cataract-treated individuals there was no significant correlation between the recalibration ability and age. Secondly, we ruled out that the post-surgical visual acuity, which is still lower than that of controls even after cataract removal (cf. Ganesh et al., 2014; Kalia et al., 2014; Maurer et al., 2006), is the only reason for the poorer recalibration behavior by showing that the group of sighted controls with experimentally reduced visual acuity still recalibrates faster than the cataract-treated individuals. This is so even when in general the recalibration rate correlates with the visual acuity after surgery for the cataract-treated individuals. Instead, the performance of the cataract-treated participants improves with time, and thus experience, after surgery, despite the lack of an analogous increase of their visual acuity over time.

Cataract-treated participants differ from sighted controls also in the development of the aftereffect after prism removal. While even the youngest controls reduce the aftereffect trial by trial, cataract-treated participants do not present a similar aftereffect decay. Since the pointing task following prism removal is performed in the absence of any visual feedback of the arm, the decline of the aftereffect highlights the contribution of proprioception (cf. Hamilton et al., 1964). Indeed, when planning and executing movements towards a visually-presented target, healthy individuals rely also on proprioception: they can aim at visually-presented targets even if their arm and hand are not in sight, given that there is a stable mapping between the visual and proprioceptive space. The aftereffect decay observed in healthy individuals would indicate that sighted controls tend to spontaneously return to their normal sensorimotor mapping, based on proprioceptive feedback. The extinction rate of the aftereffect typically increases with children’s age, with older children showing a faster decay (Gómez-Moya et al., 2016). This is a sign that sighted children learn to rely more and more on proprioception with age (cf. von Hofsten & Röslad, 1988). In contrast, cataract-treated participants do not show the same tendency to quickly reinstate the original mapping. The fact that there is no significant change of the aftereffect with time could either mean that they are simply much slower in reintroducing the original mapping, or that they are unable to integrate proprioceptive information for doing so.
Given the present findings, what could explain the recalibration performance of our cataract-treated participants? Visuomotor recalibration requires participants to establish a correspondence between the visual space and the motor space. Moreover, learning the mapping between visual and proprioceptive spaces could also contribute to the ability to recalibrate. It could be hypothesized that children who were deprived of pattern vision for the first years of life either completely lack such sensorimotor mappings, or cannot properly recalibrate them (cf. Held, 2009). The present results show that the cataract-treated participants are able to localize and reach for targets quickly after surgery in the absence of any visual distortion. Indeed, before introducing the prismatic shift (i.e., at baseline), they are able to accurately point toward the target, although they are overall less precise than controls and initially their movements seem far less adept compared with sighted individuals (cf. previous qualitative observations, Chen et al., 2016; McKyton et al., 2015). Some participants had enough residual pre-surgical vision to be able to point toward targets even before surgery, and therefore participants have either developed a sensorimotor mapping before surgery, or they were able to develop one quickly after surgery. However, despite having developed some form of visuomotor mapping, they were much less able than sighted controls to recalibrate distortions in the mapping once disturbed by prisms. Thus, the main problem seems to be in recalibrating such mappings when perturbed. Once having established an initial sensorimotor mapping, what is the information required to update such a mapping during recalibration? To recalibrate such mappings, participants need to be able to use an error signal following the introduction of a visual distortion, which is the difference between the location of the visual target and the sensed terminal hand location. The sensed terminal hand location is based on vision as well as on proprioception, and the visual distortion introduces a spatial discrepancy between vision and proprioception. Therefore, if proprioception is used, minimizing the error does not only imply changes in the visuomotor but also in the visual-proprioceptive mapping. One of the problems for cataract-treated participants to use the error signal for recalibration might therefore originate from the difficulty to establish correspondence between the visual and motor space, as well as between the visual and proprioceptive space. We recently observed an analogous problem in the development of multisensory integration after cataract removal.
Integrating signals from different senses also requires establishing correspondence between different sensory maps and thus may pose similar challenges (cf. Ernst, 2008; Held, 2009; Held et al., 2011). For instance, to be able to estimate the size of an object simultaneously explored with vision and touch, the brain needs to know the relationship between the image projected on the retina and the postural configuration of the fingers holding the object. In case of multisensory integration, we have shown that cataract-treated participants—despite other deficits (e.g., Putzar et al., 2007; Guerreiro et al., 2015)—can learn to optimally integrate multisensory signals within a few years, following a time course analogous to the one observed here.

However, the fact that cataract-treated participants learn to integrate visual and haptic information in a similar temporal window as they learn to recalibrate the sensorimotor system is not enough to conclude that these two abilities are related. Indeed, although they may share computational analogies (i.e., solving the correspondence problem), the two abilities differ in a crucial aspect: while multisensory integration requires combining sensory cues (e.g., visual and haptic), recalibration relies on the ability to combine one or more sensory cues to motor commands. In other words, while the former is a purely sensory process, the latter is a sensorimotor skill, thereby the two abilities rely on distinct neural circuits. So far, the possible relationship between these two abilities was only speculated about but could never be investigated jointly in the typically developing population. While signs of each of the two abilities emerge early in life, both abilities take years to fully mature (e.g., Contreras-Vidal, 2005; Gori et al., 2008; Hay, 1990; 1991; Nardini et al., 2008), making the study of their developmental path difficult to explore within the same participants over time. Here we had the unique chance to test 14 of the cataract-treated individuals in both studies, the multisensory integration study (Senna et al., 2021) and also this recalibration study at around the same time after surgery, allowing us to investigate the relationship between multisensory integration and visuomotor recalibration as they develop after surgery.

Strikingly, the performance of these 14 participants is significantly correlated: those who develop better post-surgical multisensory integration abilities in (Senna et al., 2021) also show a better recalibration performance in the present study (Figure 1H). This finding shows that the two abilities are indeed related: Although this is just correlational evidence, it
suggests that both tasks may indeed rely on the ability to establish correspondence between post-surgical vision and the other sensory modalities, as well as the motor commands required to reach for targets. This for the first time indicates that the development of multisensory integration and recalibration might indeed be strongly related, by showing that both abilities present an analogous developmental path following the introduction of pattern vision. Thus, we can hypothesize that it is this ability to establish correspondence between different perceptual and perceptual-motor spaces that undergoes development.

Importantly, with time after surgery cataract-treated individuals are able to learn to recalibrate their visuomotor system, even approaching the performance level of typically sighted participants. This finding indicates that visual experience is necessary for the development of the ability to recalibrate the visuomotor system, which does not mature without pattern vision and thus exposure to sensorimotor distortions. It has been suggested that sensorimotor experience has a pivotal role in the development of the recalibration ability in typically developing children. During development the internal model for such flexible sensorimotor transformations would be learned through experience, via repeated exposure to the sensory consequences of self-generated movements early in life (e.g., Bauer & Held, 1975; Bullock et al., 1993; Guigon & Baraduc, 2002; Held and Bauer, 1967). In particular, the recurrent and simultaneous exposure to proprioceptive and visual feedback while executing movements would be used to establish the correspondence between the visual space and the motor space, and between the visual and proprioceptive spaces (von Hofsten & Rösblad, 1988).

To summarize, the present study demonstrates that the lack of fine visual and visuomotor experience at an early age affects the ability of cataract-treated individuals to develop flexible sensorimotor mappings. However, the ability to recalibrate the sensorimotor system shows clear improvement over time following cataract removal, even reaching the level of controls tested with visual blur in some cases. The fact that recalibration performance in cataract-treated individuals improves with time after surgery, and not with age as it happens in sighted controls, suggests that sensorimotor experience rather than mere maturational factors (reflected by age) is central in the development of flexible sensorimotor maps. The correlation between the development of multisensory integration and
sensorimotor recalibration abilities may hint at the fact that the bottleneck for the
development may be in establishing correspondence between the sensory and motor maps.
Being able to use vision to skillfully guide actions requires a well calibrated system
and is probably the most important aspect for adept behavior, which we here show is still
able to develop with sufficient experience even after many years of visual deprivation.

Materials and Methods

Participants. Twenty Ethiopian cataract-treated children and adolescents (mean age:
13.16 years, age range: 8-20 years, 19 right-handed, mean time since surgery: 1.68 years,
range: 1 day-10 years, mean pre-surgical visual acuity: 1.37 cycles per degree, cpd, range
0.06–3.40 cpd, mean post-surgical visual acuity: 5.04 cpd, range: 1.30-13.45 cpd) took part
in the study (see Table supplement 1 for details). Participants with this condition are
extremely rare, therefore the sample size was determined by the availability of individuals
suffering with this condition: we tested all the available participants we could find over a 3
years project (N=20). They presented dense bilateral cataracts, either mature or feremature,
or else partially absorbed. Cataracts were classified as congenital, meaning they were either
present at birth or developed within the very first few months of life (Wu et al., 2016). Such
diagnosis was based on the fact that all participants showed optical nystagmus, which is
considered a signature of early onset visual deprivation (Papageorgiou et al., 2014), and their
families reported that children had bright white eyes since birth. Moreover, almost half of the
participants had a positive family history of congenital cataract (autosomal dominant), either
to one parent or older siblings, suggesting cataracts were hereditary. Furthermore, most
participants had misaligned eyes (strabismus) and some other signs suggestive of congenital
cataract, such as micro cornea or partially absorbed cataract. They underwent a complete
ophthalmological evaluation including B-scan ultra-sound to assure the retina was intact.
Inclusion criteria were isolated congenital bilateral cataracts without any other ocular or
systemic comorbidity. Participants received ophthalmological evaluation and underwent
bilateral cataract surgery and intraocular lens implantation at the Hawassa Referral Hospital,
Ethiopia. The target refraction was adjusted for far vision. On average participants were
surgically treated 11.4 years after birth (range: 5-19 years). After cataract removal, their
vision was still poorer than the normative range, which is a typical outcome of late surgical
treatment (Carlson & Hyvärinen, 1983; Ganesh et al., 2014; Hadad et al., 2012; Kalia et al.,
2014; Lewis & Maurer, 2005; Maurer et al., 2006; Ostrovsky et al., 2006; 2009, Table
supplement 1).

We had the chance to test 8 out of the 20 cataract-treated individuals also prior to
their surgery. Among them, only 4 had enough residual vision to be able to see the target and
perform the task, and were therefore tested (mean age: 12 years, range: 8-15 years, mean
pre-surgical visual acuity: 2.14 cpd, range: 1.31-2.91 cpd). We retested these 4 participants,
as well as further 9 individuals from the set described above (i.e., a total of 13 participants)
twice after surgery: the first post-surgical test took place between 1 day and 2.30 years after
surgery (mean: 6 months mean age: 12.36 years, range: 8-18 years, visual acuity: 4.97 cpd,
range: 1.30-13.04 cpd, 12 right-handed). The follow up test took place between 4 months and
1.33 year after the first test (mean: 11.52 months; visual acuity: 6.19 cpd, range: 1.35-13.72
cpd, cf. Table supplement 1 for further details).

We compared the first post-surgical performance of the 20 cataract-treated
participants to that of two control groups. The first control group consisted of 20 typically
developing sighted German participants (mean age: 13.28, age range: 8-19.5 years, normal
or corrected to normal vision, 19 right-handed), individually matched to each cataract-treated
participant for age. A second group of 20 sighted German individuals (mean age: 13.36, age
range: 8-20 years, 19 right-handed) viewed the stimuli through a blurring filter, mimicking the
poorer visual acuity exhibited by the cataract-treated participant. Thus, each participant of
this second control group was matched to a cataract-treated participant not only for age, but
also for visual acuity (group mean: 5.05, range: 1.49-14) using the procedure described in

Procedure to blur vision in sighted controls below. Control participants were randomly
assigned to either of the two control groups until the needed number of control participants in
the appropriate age-range was met for each group.

We ascertained that typically sighted German controls would not differ from typically
sighted Ethiopian individuals by comparing the performance of the two control groups (i.e.,
tested with/without visual blur) to that of two analogous control groups of typically sighted
Ethiopian participants. Eight of them (mean age: 11.13, age range: 8-15 years, all right-
handed) were tested in normal visual conditions, and 5 of them (mean age: 12.20, age range:
8-15 years, all right-handed) with visual blur. In the latter group, each control was individually
matched to one cataract-treated participant (and thus to one of the German controls tested
with blurred vision) for age and visual acuity. The pointing profile of each of the two Ethiopian
control groups in the different experimental phases overlapped with that of the corresponding
German control group. Moreover, the groups tested in similar conditions did not statistically
differ in any of the tested parameters described in the Statistical analyses section below.

Moreover, in a further experiment we aimed to explore how the ability to recalibrate
develops with age in the typically sighted population. To this end, we tested 124 German
sighted individuals with ages ranging from 6 to 35 years (mean: 13.32 years) in the pointing
task (Figure 1–figure supplement 2). To further explore the impact of age on the ability to
recalibrate in the case of visual uncertainty due to visual blur, we tested a further group of 16
German typically sighted adult participants (mean age: 28.55, age range: 12-35 years),
tested with and without visual blur (Figure 1–figure supplement 2).

Finally, a subset of 14 out of the 20 cataract-treated participants were also tested
previously in a study on multisensory perception which assessed the ability to integrate vision
with touch after cataract removal (Senna et al., 2021). Since the two tasks might share some
computational aspects that are similar (such as establishing correspondence between
sensory or sensorimotor maps), we assessed the correlation across participants’
performance in these two tasks. Participants took part in the two tasks at around the same
time after surgery (mean age: 13.67 years, range: 8-19 years, 13 right-handed; recalibration
task, mean time since surgery: 1.91 years, range: 1 day-10.44 years, mean visual acuity:
4.34 cpd, range: 1.30-12.14 cpd; multisensory task, mean time since surgery: 1.84 years,
range: 2 days-10.44 years, mean visual acuity: 4.38 cpd, range: 1.30-13.87 cpd).

Ethiopian cataract-treated and control participants took part in the experiment at the
Hawassa Referral Hospital, at the Shashamane Catholic School for the blind, or at the
Sebeta Blind School. German participants were recruited in primary and secondary schools
and at Ulm University in Germany. The study was carried out in accordance with the
Declaration of Helsinki and approved by the ethics committee of the University of Bielefeld
and Hawassa University (ref. nr. EUB 2015-139). Participants, or participants’ parents or legal guardians in case of minors, gave their written consent to the study.

Visual assessment in cataract-treated participants. The vision of the participants suffering from congenital bilateral cataract was evaluated prior to treatment and after cataract removal surgery (see Table supplement 1 for individual details). Before surgery all participants had light perception and some of them could see hand motion and additionally count fingers at very close distances. We tested their visual acuity by measuring the contrast sensitivity function (CSF) in all participants after surgery and in a subset of 16 before surgery (cf. McKyton et al., 2018; Senna et al., 2021). The remaining 4 were not tested before surgery, either because they had too poor visual acuity to be able to perform the CSF test, or because the procedure was not available at the time they were surgically treated. The subtle variability in pre-surgical visual acuity across participants can be partially explained by the fact that long-standing congenital cataracts can be partially absorbed, thus leaving islands of aphakic clear vision whereas totally white cataract enables light perception only.

The post-surgical CSF was assessed always in the same experimental session as the main experiment. In this test, participants saw a series of Gabor patches (sinusoidal gratings of different spatial frequencies and contrast levels with 19.5 cm Gaussian envelope) presented on a 15.6” gamma-corrected computer display (1920 x 1080 pixels resolution). Participants rested their head on a chin-rest at 30 cm distance from the display and had to report whether the grating was oriented horizontally or vertically on each trial. Some participants with extremely poor vision were allowed to perform the test at a shorter distance (15-20 cm) since they would have not been able to perform the task otherwise. In a first block, gratings were all presented at 100% contrast. The test started with a grating at the lowest spatial frequency (0.042 cpd = 1 cycle per 512 pixels at 30 cm viewing distance). As long as the participant’s response was correct, a grating with the next higher spatial frequency was presented (up to 10.75 cpd = 1 cycle per 2 pixels). When the participant made the first mistake, a staircase procedure was introduced: 3 correct responses in a row led to the next higher frequency, while 1 mistake led to the next lower frequency (i.e., 3 up-1 down staircase). We used a total of 9 spatial frequencies evenly spaced on a logarithmic scale. The procedure stopped after 6 reversals. In a second block, each of the spatial frequencies was
kept constant while the contrast was varied. The frequencies were tested separately one
after the other, from the lowest to the highest, starting one frequency step higher than the
spatial threshold frequency assessed in the first block. For each spatial frequency, the first
grating was presented at 100% contrast. As long as participant’s responses were corrected,
the contrast was gradually reduced (to a minimum of 0.78%). Upon the first error, a 3 up-1
down staircase procedure similar to the one in the first block was used, to measure
participant’s contrast threshold at each frequency, calculated as the average contrast of the
last 6 reversals. A total of 8 contrast levels (equally spaced logarithmically) was used. For
each frequency, we took the logarithm of the sensitivity (1/contrast threshold) and plotted it
as a function of spatial frequency (also log-transformed), yielding the patient’s CSF. The CSF
was fitted with an inverse parabola (McKyton et al., 2018; Senna et al., 2021; Watson &
Ahumada, 2005) to get the CSF cutoff frequency, namely the highest spatial frequency that
the participant could still see at the maximal contrast. According to this assessment, most
participants were classified as suffering from legal blindness or severe low vision before
surgery. According to the guidelines of the World Health Organization (WHO 2010,
International Classification of Diseases, 10th revision), legal blindness is defined as visual
acuity below 20/400 (corresponding to a 1.5 cpd cutoff frequency). Instead, the National
Institute of Health of the United States (NIH), classifies a visual acuity below 20/200 (i.e., 3
cpd cutoff frequency) as legal blindness. Importantly, most participants improved after
surgery (log-transformed pre- vs. post-surgical CSF, t15=3.7, p=0.002) and transitioned out of
the category of legal blindness. On average, cataract-treated individuals showed a CSF
cutoff frequency of 5.04 cpd (range: 1.30–13.45 cpd). The subset of participants who had
their visual acuity tested already before surgery had a mean CSF cutoff frequency of 1.37
cpd (0.06–3.4 cpd).

Procedure to blur vision in sighted controls. To investigate whether any possible difference in
the performance in the pointing task between cataract-treated and sighted individuals might
simply result from the lower visual acuity exhibited by the former, we blurred vision in a group
of 20 sighted individuals, to mimic the poor visual acuity that the cataract-treated participants
still experienced after surgery. To this end, we placed a transparent Plexiglas panel covered
by a blurring transparent plastic foil on top of the setup used during the task (see Figure 1A).
Changing the distance between the blurring screen and the visual targets varied the amount of blur applied to the visual target, with a greater blurring factor for greater distance. We ran a pilot study to select the range of distances between the screen and the visual target that would be needed in order to reproduce the visual acuity of the cataract-treated participants in terms of experienced blur levels and contrast reduction. We made sure to obtain analogous CSF cutoff frequency values and an analogous shape of the contrast sensitivity function in the matched control participants. The CSF of the control participants was measured by placing the blurring panel at the desired distance from the computer’s monitor. Each sighted control was individually matched to a cataract-treated participant for visual acuity (mean CSF: 5.05 cpd, range: 1.49-14 cpd) and age (mean age: 13.4 years, range 8-20 years).

**Experimental procedure.** Participants sat at a table, in front of the box-like setup (27 cm high, 76 cm wide, 37 cm deep), placed on the edge of the table. The side of the box proximal to the participants was open, so that participants could place their arms inside. Thus, the upper side of the box hid the participant’s arm from sight (see Figure 1A). Depending on the length of the participant’s arm, the depth of the box could be adjusted, from 37 to 30 cm. Subjects were instructed to repeatedly point towards a visual target (the red cap of a marker, 3.5 cm high, 1.6 cm wide) placed at the distal side of the box. They were asked to point with their dominant hand fast but with a comfortable speed. Participants performed the movements inside the box, and after each pointing they returned their hand to a starting position aligned to their mid-sagittal axis. The target was presented manually by the experimenter at the distal side of the box, right above its edge (around 40-50 cm from the participant’s eye). In each trial, the target could be shown at one of three possible locations: straight ahead in front of the subject (0°), 25° to the left or to the right of the participant’s body midline. At the back of the box a ruler was attached such that the experimenter could determine and record the participant’s pointing location (cf. Fortis et al., 2010; Frassinetti et al., 2002 for a similar procedure). Participants’ head was kept aligned with their body’s sagittal axis by a chin-rest, and the experimenter made sure that the participant would not move the head during the experiment.
The experiment consisted of three phases. During the pre-prism phase, participants performed 12 pointing movements (4 for each target location). The far side of the box was closed by means of a removable semi-transparent Plexiglas® panel in order to prevent participants from seeing their finger reaching out of the box at the far side. Therefore, the task was performed in the absence of any visual feedback of the hand and finger movement. In this pre-prism phase, participants wore plastic goggles without any distorting lens and thus they had a natural view on the scene. In the next phase (prism), a prismatic lens was introduced into the goggles, shifting the visual field by 20 prism diopters (i.e., 11.31°) toward the right. In this phase the Plexiglas panel was removed and subjects performed 48 pointing trials (16 for each target location) with terminal visual feedback of their fingers position. That is, since the movement was executed below the top of the box, participants could only see the tip of their finger emerging from the distal edge of the box (terminal feedback). In this way, participants could not correct the movement along the way, but only in the next trial based on the terminal pointing error. In the last phase (post-prism), the prism lens was removed and the Plexiglas panel was reintroduced, as in the pre-prism phase, and participants performed 48 trials (16 for each target location) again without terminal visual feedback. In each phase, targets were presented in a pseudorandom order, with the same number of trials for each of the three target positions. Overall, the experiment consisted of 108 trials and lasted about 20 min.

Participants were tested monocularly. Cataract-treated participants were tested with their better eye based on medical examination and participants’ self-reports. Sighted subjects were tested with their dominant eye as determined by the hole-in-the-card test (Durand & Gould, 1910). Out of all participants, 13 cataract-treated participants, 11 sighted controls tested with normal vision condition, and 10 controls tested with blurred vision were left eye dominant.

Statistical analyses. Performance in the pointing task was assessed by examining pointing errors, as the difference—in degrees of visual angle—between the recorded pointing position and the location of the target. A negative score indicated a leftward error with respect to the target, while a positive score indicated a rightward error. To quantify error reduction in the
prism phase, in each group we fitted a power function on the mean pointing errors across the participants of each group across all trials of the prism phase ($Error = a \times x^b$, see main text). Note that the individual profiles in sighted participants were best described by exponentials. However, due to noise in the individual profiles of the cataract-treated participants, the curves were fitted on the group mean, and the mean of multiple exponentials with different rate parameters typically approximates a power function.

To compare the error made in the pre-prism baseline and in the post-prism phase across the three groups, we calculated the mean pointing error across all trials of each of the two phases in each participant. For each phase, we compared the mean pointing error across the three groups using a Kruskal–Wallis test, followed by pairwise comparisons carried out with Bonferroni-corrected Wilcoxon-Mann-Whitney tests (see main text). We set the significance level alpha to 0.05. Note that non-parametric tests were used here and elsewhere in the text whenever the normality assumption was violated.

To analyze individual recalibration performance, we calculated a recalibration index ($i_{recal}$) within each participant. This index combined the amount of recalibration in the prism and post-prism phases (Prism Recalibration and Aftereffect, respectively, cf. Eqn. 2 of main text). This was done by averaging the error reduction in the prism phase (induced Prism Distortion, 11.31°, minus End Prism, i.e., average of the last three pointing errors of the prism phase, cf. Fortis et al. (2010)) with the (negative) magnitude of the aftereffect exhibited right after prism removal (Start Post Prism, i.e., average of first three pointing errors of the post-prism phase). The result was normalized to the prism distortion, leading to an index ranging between 0 and 1, with higher $i_{recal}$ indicating stronger recalibration (cf. Eqn. 2):

$$i_{recal} = \frac{1}{Prism \text{ Distortion}} \cdot \frac{Prism \text{ Distortion} - \text{End Prism}}{\text{Start Post Prism} - \text{End Prism}}$$

The two components of this index (Prism Recalibration and Aftereffect) were significantly correlated across all participants (Pearson $r=0.39$, $p=0.002$): the greater the error reduction in the prism phase, the greater the magnitude of the subsequent aftereffect.

In cataract-treated participants we correlated $i_{recal}$ with the factors age at test and age at surgery, time since surgery, and visual acuity (i.e., the log-transformed CSF cutoff frequency, Figure 1C) via Pearson’s correlation coefficient. Time since surgery and age were correlated ($r=0.48$, $p=0.036$). For each factor the outliers, defined as values 2.5 standard
deviations from the mean, were excluded from the analysis. This led to excluding 2683 participants from the analysis on the time since surgery. Analyses were performed with MATLAB.

Data Availability

The full dataset including all the experimental results and the participants' demographic information has been deposited on Mendeley: doi:10.17632/ksdwxdwtxg.2. For a preview before the paper is accepted for publication, please visit: https://data.mendeley.com/datasets/ksdwxdwtxg/draft?a=6d65f8db-5a7a-4c95-8468-5dfa36ebfa71

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**Figure 1–Table supplement 1.** Clinical characteristics of the cataract-treated participants.

**Figure 1–Figure supplement 1.** Details on the performance in pre-prism and post-prism phases.

**Figure 1–Figure supplement 2.** Development of recalibration in the typically sighted population.

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**Figure 1–Figure supplement 1. Performance in the pre-prism and post-prism phases.**

(A) Performance in the *pre-prism* phase. To assess whether cataract-treated participants were able to correctly perform the pointing task during the *pre-prism* phase (i.e., before introducing the prism lens) for all target locations, for each participant we plotted each response against each target location (-25°, 0°, 25°) and we fitted a linear regression to the data. The overall linear regression was $y = 1x - 0.57$ (where the parameters are the mean slope and mean intercept in the group of cataract-treated participants). The fact that the mean regression slope was 1 (range 0.92-1.30) indicates that cataract-treated individuals could correctly perform the task for the different target positions. In the left panel, red dots indicate the locations of all pointing responses as a function of targets' locations, which have been slightly jittered for graphical clarity. The thick black line and the light-gray shaded area represent the linear regression and its associated 95% confidence intervals, respectively.

The right upper and lower panels show accuracy and precision, respectively, in the *pre-prism* phase in the three groups (red: cataract-treated individuals, light-blue: sighted controls tested with visual blur, blue: sighted controls tested without visual blur). The mean pointing error shown by cataract-treated participants (upper panel) did not differ from that of the two controls groups (i.e., the accuracy in the *pre-prism* phase was comparable among cataract-treated, mean±SEM, 0.58±0.42, sighted 0.35±0.23, and sighted participants tested with visual blur, 0.19±0.26, Kruskal–Wallis test, $\chi^2(2)=1$, $p=0.61$, $\eta^2=0.017$). The precision of participants' pointing during the baseline was calculated as the variance of the residuals (lower panel): in each participant, we obtained the residuals by calculating the median pointing error, and subtracting it from individual pointing trials. A Kruskal-Wallis test run on the variance of the residuals in the three groups revealed a significant effect of group ($\chi^2=11.36$, $p=0.003$, $\eta^2=0.181$). Bonferroni-corrected pairwise Wilcoxon-Mann-Whitney tests...
showed that cataract-treated participants were overall less precise (i.e., their residuals presented a higher variance: 10.71±2.87 deg$^2$) than controls tested in normal vision conditions (2.41±0.21 deg$^2$; p=0.005) or with visual blur (3.17±0.42 deg$^2$; p=0.025). The two control groups did not statistically differ from each other (p=0.39). Thus, cataract-treated participants were able to perform the pointing task before wearing the prismatic goggles: they showed a similar accuracy to controls, but they were overall less precise. (B) Development of the aftereffect throughout the post-prism phase. In each group we fitted the mean error profile of the group across all trials of the post-prism phase with both a power function ($\text{Error} = a \times x^b$) and a linear fit ($\text{Error} = a + b \times x$). Power functions provided a better fit for both control groups. Sighted participants tested either in normal visual condition or with visual blur reduced their aftereffect during the post-prism phase (recalibration rate $b$=-0.11, CI=[-0.13, -0.08] and $b$=-0.04, CI=[-0.07, -0.01], respectively). Instead, the error profile of the cataract-treated group, which was more noisy, was more robustly captured by a linear fit, which showed that the pointing error was constant during the post-prism phase (i.e., cataract-treated participants did not significantly reduce their aftereffect, as shown by the fact that the CI=[-0.01, 0.04] for $b$=0.013 included 0). Individual dots and thick lines represent group mean pointing errors and curve fits, respectively, for each group: cataract-treated (red), sighted tested with (light blue) and without (blue) visual blur. The decay of the aftereffect observed in typically sighted participants is in line with previous evidence showing that the aftereffect tends to decline even in the absence of visual feedback and motor activity (Hamilton & Bossom, 1964). Sighted controls tend to spontaneously return to the normal sensorimotor mapping, after prism recalibration has taken place. Cataract-treated participants do not show the same tendency to quickly reinstatate the original mapping. Instead, they show a behavior that in the sighted population is typical of much younger children than them. Indeed, the extinction rate of the aftereffect increases with age in the typically developing population, with older children showing faster decay (Gómez-Moya et al., 20016). The youngest sighted control participants we tested (11-6-7 year-old, see also Figure supplement 2) already reduced their aftereffect during the post-prism phase (power function fit: recalibration rate $b$=-0.1, CI=[-0.17, -0.03]), unlike the cataract-treated participants. Thus, our cataract-treated group shows a behavior which seems to be less mature than the one of their age-matched sighted peers. Error bars represent SEM.
Figure 1–Figure supplement 2. Developmental path of recalibration in the typically sighted population. (A) Mean pointing errors across the three phases in different age groups. We explored how the ability to recalibrate visual distortions develop with age in the typically sighted population by testing 124 German sighted individuals (mean age: 13.32, range: 6-35 years, 115 right-handed) in the same pointing task described in the main text (Figure 1B). Participants were tested in normal visual conditions (i.e., without visual blur). Results are binned into 2-year age groups. The inset shows individual $i_{recal}$ values (a measure of recalibration in both the prism and post-prism phases, see main text). Age positively correlated with $i_{recal}$ ($r=0.30$, $p=0.0007$): the older the participant, the faster the recalibration rate. (B) Effect of visual blur on recalibration performance in adults. We further explore the impact of age on the ability to recalibrate the visuomotor system in case of uncertainty about reaching error due to visual blur (Burge et al., 2008), by testing a further group of 16 adults (mean age: 28.55, range: 21-35 years, 14 right-handed). They were tested in two sessions, two days apart, in counterbalanced order across participants: one with and one without visual blur. They were tested with an amount of visual blur comparable to that of the cataract-treated group on average (mean CSF cutoff frequency: 5.07 cpd, range: 1-18.55). The figure shows mean pointing errors of adult participants in these two sessions and the performance of the children and adolescents tested with visual blur (see Figure 1B) for comparison. $i_{recal}$ was slightly but significantly smaller in blurred-vision adults ($0.68 \pm 0.03$) as compared to adults tested in normal visual conditions ($0.74 \pm 0.02$, t-test, $t_{15}=2.23$, $p=0.04$). However, sighted adults tested with blurred vision still recalibrated faster than the sighted children and adolescents tested with an analogous visual blur: $i_{recal}$ in the blurred-vision adults was significantly greater than that of blurred-vision children and adolescents ($0.57 \pm 0.03$, t-test, $t_{35}=2.67$, $p=0.01$). Instead, no difference was found between the sighted adults and the sighted children and adolescents tested in normal vision conditions reported in the main text ($t_{35}=1.51$, $p=0.14$).

Figure 1–Table supplement 1. Clinical characteristics of the cataract-treated participants. Participant ID, sex, age at test, pre-operation visual assessment, visual acuity (measured as contrast sensitivity function (CSF) cutoff frequency in cycles per degree (cpd)) before and after surgery, and time since surgery at test (years (y), months (m), days (d)). In the pre-surgical visual assessment, $LP$ indicates only light perception, followed by hand motion perception ($HM$), and the ability to count fingers up to the specified distance ($FC$). We report the highest measure participants could perform with both eyes, unless otherwise
specified (RE: right eye, LE: left eye). We did not test the visual acuity of 4 participants before surgery, either because they had too poor visual acuity to be able to perform the CSF test, or because the procedure was not available at the time they were surgically treated. We assessed the post-surgical CSF cutoff frequency in the same experimental session as the experimental task. Some participants were tested in the study multiple times, before and/or after surgery. We do not have information regarding the exact date of surgery of two participants, because they were included in our project only after surgery, and not operated by our team. Both of them were surgically treated more than 2 years before taking part in the present experiment.
A

Sighted controls

- 6-7 y
- 8-9 y
- 10-11 y
- 12-13 y
- 14-15 y
- 16-17 y
- Adults

Prismatic drift

Error (deg)

B

- Adults
- Adults blur
- Children blur (main text)

Prismatic shift

Pointing Error (deg)

* *

Trial number

Pre → Prism → Post

Pre → Prism → Post
| ID | Sex | Age (year) | Pre-op visual assessment up to | Pre-op CSF cutoff (cpd) | Post-op CSF cutoff (cpd) | Time since surgery (y,m,d) |
|----|-----|-----------|-------------------------------|-------------------------|--------------------------|---------------------------|
| p1 | m   | 12.6      | HM                           | unknown                 | 8.24                     | unknown                   |
| p2 | m   | 14.4      | unknown                      | 13.04 / 13.72           | unknown/ 4m later         | 10.4 y                    |
| p3 | f   | 15.4      | unknown                      | 3.48                    | 10.4 y                   |                           |
| p4 | f   | 19.4      | unknown                      | 2.47                    | 2.3 / 2.8 y               |                           |
| p5 | f   | 18.3      | HM                           | 0.44                    | 2.1 / 3.4 y               |                           |
| p6 | m   | 14.1      | FC 3m                        | 3.40                    | 2.1 / 3.4 y               |                           |
| p7 | m   | 10.1      | RE: FC 1.5 m/ LE: No LP      | 1.90                    | 1.1 y                    |                           |
| p8 | m   | 11.1      | RE: FC 50 cm/ LE: No LP      | 2.53 / 1.49             | 1.1 / 1.6 y               |                           |
| p9 | m   | 11.1      | LP                           | 0.66                    | 1.1 y                    |                           |
| p10| f   | 20.6      | FC 10 cm                     | 0.74                    | 1.9 y                    |                           |
| p11| m   | 11.1      | HM                           | 1.01                    | 1.9 / 6.4 m               |                           |
| p12| f   | 13.4      | HM                           | 0.60                    | 1.9 m                    |                           |
| p13| m   | 9.1       | HM                           | 0.71                    | 1.9 / 6.4 m               |                           |
| p14| f   | 10.1      | HM                           | 2.03                    | 1.9 / 6.4 m               |                           |
| p15| m   | 9.0       | RE: FC 20 cm/ LE: No LP      | 0.60                    | 3 d / 4.3 m               |                           |
| p16| m   | 15.0      | HM                           | 1.50                    | - 2 d / 3 d / 4.3 m       |                           |
| p17| f   | 8.0       | FC 1m                        | 1.31                    | -2 d / 2 d / 4.3 m        |                           |
| p18| f   | 10.6      | FC 3 m                       | 2.84                    | -2 d / 2 d / 4.3 m        |                           |
| p19| f   | 15.0      | FC 2m                        | 2.91                    | -2 d / 1 d /4.3 m         |                           |
| p20| m   | 15.0      | LP                           | 0.08                    | 1 d / 4.3 m               |                           |