**Postural stability and optic flow sensitivity following sight restoration from congenital bilateral cataracts**

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**Abstract**

Vision is crucial for maintaining balance and facilitating locomotion. Optic flow, for example, provides key self-motion cues for navigation. Congenital blindness typically leads to increased postural sway and impaired navigation. Here we investigated postural stability and optic flow sensitivity in individuals surgically treated for congenital dense bilateral cataracts years after birth. Experiment 1 assessed whether cataract-treated participants rely on vision to stabilize their stance with eyes open compared to closed. Cataract-treated participants decreased their sway with open eyes to a lesser extent than controls, indicating a reduced ability to use vision for stabilization. Interestingly, participants tested longer after surgery showed less sway, suggesting partial learning in utilizing vision to enhance stability. Experiment 2 assessed whether different radial and translational optic flow patterns elicit distinct effects on body sway, which would indicate illusory sensorimotor perceptions. We included typically sighted controls tested either with normal vision or with experimentally reduced visual acuity. While cataract-treated participants exhibited greater sway than controls, their sway was less influenced by optic flow patterns.

Overall, the study showed that cataract-treated individuals exhibit partial learning in utilizing vision for stabilization and less pronounced illusory self-motion perception from optic flow compared to typically sighted individuals.

**Introduction**

Efficient locomotion and navigation rely on the integration of visual, vestibular, and proprioceptive cues for balance and self-motion perception. In particular, visual inputs are crucial for guiding actions, such as interacting with objects or navigating the environment. The absence of visual input early in life, as in congenital blindness, typically affects the development of locomotion and mobility skills. For instance, the onset and development of important motor abilities, such as rolling, crawling, standing, balancing, and locomotive skills, are usually delayed [1–3]. Likewise, blind infants show delays in head and postural control, with a prolonged period of ataxic features, possibly resulting from the absence of visual calibration on proprioceptive and vestibular systems [4,5]. Postural stability is also impaired by visual deprivation, as indicated by larger postural sway during upright standing in blind children and adults compared to sighted individuals using vision [6-11]. Even moderate visual impairment, such as partial visual loss, amblyopia, or strabismus, can impact postural stability [12–14]. Supporting this, a recent independent study reported reduced postural control in cataract-treated participants, evidenced by shorter single-leg stance times [15]. The pivotal role of vision in motor control during upright standing is evident also in typically sighted individuals: when tested with closed eyes, their postural stability deteriorates to levels similar to those observed in blind individuals [16–18,7,9]. In visually impaired children and adults, such deficits in postural control and balance typically result in slower walking speed and more prolonged stance duration compared to sighted controls. This potential cautious walking strategy appears to be adopted to mitigate the elevated risks of falling [19].

Vision offers an essential contribution to orientation and wayfinding, providing continuous updates on one's position within the environment. Visual cues, like optic flow, play a key role in this process [20,21]. Optic flow refers to the apparent motion observed in the visual scene as one moves, representing the perceived movement of objects relative to the observer's motion. This flow offers valuable self-motion cues that aid navigation, including information about heading direction, speed, distance, and layout of surfaces [22,23]. In the case of visual deprivation, navigating and wayfinding rely predominantly on vestibular and proprioceptive cues, and blind individuals often exhibit significant challenges in remembering locations and constructing accurate spatial maps [24–29].

In sighted individuals, exposure to optic flow patterns while standing can induce an illusory perception of self-motion, often leading to postural instability [30–32]. This happens because the brain interprets this information as if the observer is moving forward, even when they are stationary. The mismatch between the visual perception of movement and the lack of actual physical movement can lead to postural adjustments, as the body attempts to maintain balance in response to perceived motion. This reaction is already present in few-day-old newborns, who respond to backward optic flow by leaning their heads backwards [33]. Whole body swaying is later found in infants [34–36], children [37], and adults [37,38].

The present study assessed postural stability and sensitivity to optic flow in individuals with congenital dense bilateral cataracts who underwent sight restoration surgery several years after birth. In Experiment 1, we investigated whether cataract-treated participants rely on vision to stabilize their stance. If this is the case, they were expected to reduce their sway when tested with eyes open compared to closed. In Experiment 2, we assessed whether different radial and translational optic flow patterns would elicit distinct effects on their body sway, potentially indicating the ability of these patterns to induce an illusory percept of self-motion. According to Gibson’s theory of direct perception [20], the observer's visual system directly perceives and interprets the changing patterns of optical flow, without requiring complex cognitive processing and inferences. Even infants demonstrate the ability to discriminate between different optic flow patterns and exhibit postural reactions, suggesting that learning may not be necessary for developing sensitivity to optic flow [33,39–41]. However, several studies show a gradual improvement in the sensitivity to optic flow with age during infancy and childhood. For instance, motion coherence thresholds for optic flow corrupted by noise improve with age [39,42–45]. This finding suggests that experience, particularly with self-produced mobility, may contribute to the development of visual abilities to process optic flow related to self-motion [35]. This development might depend also on maturational factors, such as changing height and locomotion speed resulting from physical growth [46]. Similarly, the progressive improvement in radial motion sensitivity could reflect the maturation of cortical motion mechanisms within the dorsal pathway, specialized in detecting radial motion [40].

Previous evidence has shown that cataract-treated individuals display marked deficits in perceiving global motion, even when treated surgically as early as 3 months of age [47–49]. When asked to discriminate the direction of coherently moving dots in the presence of randomly moving noise dots, their coherence thresholds are, on average, five times poorer than those of typically sighted controls [47]. The fact that such a brief period of deprivation can permanently alter global motion sensitivity suggests that the sensitive period for damage is very short, likely around birth [50]. This deficit cannot be attributed to a general difficulty in segregating signal from noise in moving elements, as cataract-treated individuals do not exhibit analogous impairments in biological motion perception [51,48]. It is possible that, like biological motion, also optic flow perception may be mediated by spared mechanisms. Indeed, radial motion perception appears to rely on specialized detectors and a distinct region within the V5/MT complex, separate from those responding to other types of motion [52,53].

We conducted two experiments to assess postural stability under closed versus open eyes conditions and the effect of different optic flow patterns on body sway in a group of Ethiopian participants diagnosed with congenital dense bilateral cataracts who underwent surgical intervention years after birth. Their postural stability (Experiment 1) was compared to an age-matched typically sighted group, while their sensitivity to optic flow (Experiment 2) was evaluated also against a second control group with experimentally reduced visual acuity to match the cataract-treated cohort.

**EXPERIMENT 1: POSTURAL STABILITY**

**Methods**

*Participants*

Eleven Ethiopian cataract-treated participants (age, mean±SD: 12.26±3.02 years, time since surgery, TSS: 1.13±0.49 years; height: 144.73±12.92 cm) and 12 German typically sighted age-matched controls (12.85±1.91 years, 157.33±10.17 cm) participated in the experiment. Additionally, to control for sociocultural factors, we collected data from a small sample of typically sighted Ethiopian participants in both experiments, which yielded results comparable to the German controls (Figure S3). Before surgery and right before taking part in the experiment, we evaluated participants’ visual abilities (Supplementary Materials). We assessed their spatial visual acuity by measuring their contrast sensitivity function (CSF) cut-off frequency. Preoperatively, the CSF cut-off frequency was, on average, 1.36±1.67 cycles per degree, cpd. Based on this measure, the majority of participants were classified as experiencing legal blindness or severe low vision. Following surgery, visual acuity significantly improved (mean±SD: 5.19±3.43 cpd, pre vs post, Wilcoxon signed-rank test, W=65, p=0.002), with most participants transitioning out of the legal blindness category (see Table S1 and Figure S1 for individual details).

Ethiopian Participants received treatment at the Hawassa Referral Hospital. They completed the tasks at the hospital, the Shashamane School for the Blind, or the Sebeta School for the Blind, while German participants were tested in primary and secondary schools. The study protocol was approved by the ethics committee of the University of Bielefeld, Germany (EUB 2015-139) and Hawassa University, Ethiopia. Written consent was obtained from the parents or legal guardians of all participants.

*Procedure*

Participants stood on a foam pad placed on a Nintendo Wii Balance Board (Figure 1, left), a commercial force-sensing platform equipped with four force sensors, capable of accurately detecting weight distribution and shifts in the centre of pressure. The use of this low-cost platform has been previously reported to provide reliable postural data, comparable to that obtained using laboratory-grade force platforms (e.g., [54]). The foam pad (Airex Balance Pad, Airex AG, Sins, Switzerland, 41x50x6 cm, 55 kg/cm3) was used to increase the difficulty of the balance task [54,55]. Participants were instructed to stand barefoot on the foam pad, in a comfortable position, with their feet spaced hip-width apart (approximately 20 cm) and their arms relaxed at their sides. Two parallel stripes were marked out on the foam pad, to guide participants’ foot placement, ensuring they positioned their feet approximately at the required distance and close to the centre of the balance board. Participants were instructed not to move their body or their head. Their static balance was recorded under two conditions: with eyes open and closed. In the closed-eyes condition, participants were blindfolded to prevent any visual input, even if they briefly opened their eyes. The order of the two conditions was counterbalanced across participants, with each condition lasting 40 s, in line with previous studies recommending a recording duration of around 30 s to obtain reliable measures of the CoP [56]. Data was recorded with a sampling rate of 30 Hz.

*Statistical analyses*

Body sway was assessed by determining the area (in cm2) of the 95% prediction ellipse for each participant and condition [54,57–59]. This ellipse represents the region that, with 95% probability, contains the centre of CoP sway points, assuming the points are distributed according to a bivariate normal distribution (Figure 1, left). It provides a measure of the dispersion of CoP data, with a larger ellipse area indicating greater postural instability. We ran a mixed ANOVA on log-transformed areas with the within-participant factor condition (open, closed eyes) and the between-participant factor group (cataract-treated, sighted).

**Results**

The ANOVA revealed a significant condition by group interaction (F(1,21)=25.7, p<0.001). Bonferroni-corrected planned comparisons indicated that both sighted controls and cataract-treated participants significantly reduced sway with open eyes compared to closed eyes (controls, open eyes, median±mean absolute deviation, MAD: 14.07±6.90 cm2, closed eyes, 50.69±21.83 cm2, p<0.001; cataract-treated, open eyes: 44.32±13.45 cm2, closed eyes: 51.25±14.38 cm2, p=0.038, see Table S2 for log-transformed values). However, cataract-treated participants did not reduce their sway as much as sighted controls: while the two groups did not differ in body sway with closed eyes (p=1), cataract-treated participants significantly swayed more than controls with their eyes open (p=0.001, Figure 1, middle). Furthermore, we found significant main effects for group (F(1,21)=7.46, p=0.013), indicating greater sway in the cataract-treated group and condition (F(1,21)=74.9, p<0.001), indicating greater sway with closed eyes, though these effects must be considered in the context of a significant interaction, which reveals that the relationship between condition and sway varies across groups.

To explore potential factors influencing the performance of cataract-treated participants at the individual level, we correlated performance (i.e., body sway with open or closed eyes) with age at test, age at surgery, height, visual acuity, and time since surgery using Pearson's correlation coefficient. Age–at test and at surgery–and visual acuity were log-transformed to reduce skewness in their distribution and to linearize their relationships with the sway parameter. Participants tested longer after surgery exhibited a smaller sway area in the closed eyes condition (r=-0.70, p=0.017, Figure 1, right). Although a similar trend was observed in the open-eyes condition (Figure 1, right), the effect was not statistically significant (r=-0.521 p=0.10, Figure 1, right). No other factor significantly affected performance with either eyes open or closed. In contrast, controls exhibited an increase in sway correlated with height in the condition with eyes closed (r=0.68, p=0.015; notably, age and height were correlated r=0.78, p=0.003, as in cataract-treated participants, r=0.88, p=0.0003). These correlations were not observed in the eyes open condition, where performance did not correlate with either height or age. It is important to note that we did not apply corrections for multiple comparisons to this set of correlations: while such corrections can reduce Type I errors, they increase the risk of Type II errors, potentially masking significant correlations, especially with small sample sizes. To provide a more complete assessment of the evidence for the alternative versus null hypotheses, we also conducted Bayesian regression analyses, which are reported in the Supplementary Materials.

**Discussion**

Cataract-treated participants showed reduced body sway with eyes open versus closed, indicating some reliance on vision for stabilization. However, their ability to use visual input for stabilization was less efficient than that of typically sighted controls. Immediately after surgery, there was already a difference in sway between the closed and open eyes conditions, possibly due to pre-surgical residual vision (Figure 1, Table S1). Nonetheless, participants tested longer after surgery showed less sway, suggesting potential learning in using the improved vision for stabilization. This was especially evident in the closed-eyes condition, suggesting a continuous refinement in the ability to utilize visual cues for stabilization that extended to situations without visual input. The other factors considered, namely age at test or surgery, visual acuity, and height, do not seem to influence performance. However, due to the small sample size and the heterogeneity of the group, all these correlations should be interpreted with caution and a larger sample would be needed to drive more reliable conclusions. Unlike cataract-treated participants, sighted controls showed greater sway in the eyes-closed condition with higher height, probably because with higher height (correlated with age), their centre of mass is higher, leading to increased body sway. Notably, this effect was not observed in the eyes open condition, indicating that even at the youngest age tested, controls were already able to effectively utilize visual cues for stabilization. Previous research on typically sighted individuals indicates that postural sway, tested with eyes open, decreases with age during childhood [60]. In our study, we did not observe a similar decline, although this discrepancy may be attributed to the limited size of our sample.

**EXPERIMENT 2: OPTIC FLOW**

**Methods**

*Participants*

We tested 13 cataract-treated participants (12.13±3.00 years, 5.20±3.18 cpd, TSS: 1.28±0.71 years, 144.31±11.95 cm) and two control groups. The first control group (Sighted) consisted of 13 age-matched sighted individuals tested in normal visual conditions (12.39±2.85 years, 156.17±16.26 cm). As previous studies show that poor vision reduces postural stability, we assessed whether simply reducing visual acuity in sighted controls could result in performance comparable to that of cataract-treated participants. To this end, we introduced visual blur in a second group of 12 age-matched sighted individuals (Blurred), adjusted to a level comparable to that of the cataract-treated group (12.85±1.95 years, 157.33±10.17 cm, 7.21±2.19 cpd, see Supplementary Materials for the blurring procedure).

Finally, we tested a larger group of 42 typically sighted participants ranging in age from 7 to 34 years under standard visual conditions (14.75±6.4 years, 157.37±17.52 cm). This allowed us to investigate whether we could capture any possible developmental trend related to age within our setup, stimuli, and procedure. Eleven of the 13 cataract-treated participants and all blurred-vision controls also participated in Experiment 1 (Table S1).

*Stimuli*

The stimuli were generated in Unity and presented on a gamma-corrected 15.6-inch monitor (1920 x 1080 pixels resolution, 60 Hz refresh rate). Stimuli consisted of limited lifetime moving dots. In each condition, there were 300 white dots per frame moving against a black background with a speed of 18°/s. Dot size varied from 0.1° to 0.6°, and dot density was approximately 18.75 per 60 pixels. Each dot had a lifetime ranging from 10 to 333 ms to prevent participants from tracking individual dots. These parameters were selected based on prior research investigating global motion perception in cataract-treated individuals [51,53]. Three optic flow patterns were shown: radial expanding, radial contracting, and translational (either left-to-right or right-to-left, see *Body sway task*). In a static condition, participants observed a field of 300 static dots.

*Procedure*

*Discrimination task*

Before the experiment, we verified that cataract-treated participants had sufficient visual discrimination ability to distinguish different optic flow patterns. Only those who could differentiate between expanding and contracting optic flow with at least 75% accuracy were included in the study (Supplementary Materials). Of the 13 participants included in the study, 9 achieved 100% accuracy, 1 reached 95%, 2 had 85%, and 1 showed 75% accuracy. We tested 2 further participants (age: 9 and 11 years; TSS: 2 days, visual acuity: 1.85 and 0.17 cpd), but they were not included in the study due to low discrimination accuracy (55% and 60% correct responses, respectively).

*Body sway task*

Participants stood barefoot on the foam pad positioned on the Wii Balance Board, maintaining a hip-width distance between their feet, and their arms resting comfortably at their sides. The centre of the screen was positioned at participants’ eye level and aligned with the centre of their head. Participants were positioned 30 cm from the center of the monitor, allowing the screen to cover approximately 60 degrees of visual angle horizontally and 36 degrees vertically. This close positioning was chosen to maximize visual field coverage, ensuring a stronger and more effective impact of the optic flow. Due to the common occurrence of amblyopia and lack of binocular vision in late cataract-treated individuals [61], and typical deficits in optic flow perception associated with amblyopia [62], participants were tested monocularly. Cataract-treated participants used their better eye, as determined by medical assessment and self-reports. Controls used their dominant eye, as determined through the hole-in-the-card test [63]. Participants were instructed to maintain a relaxed stance and to look straight ahead, avoiding head movements or fixating on individual dot trajectories. At the beginning of each condition, a large white dot was displayed at the centre of the screen. The experimenter started each condition by clicking on the dot through the touchscreen, ensuring the next condition started only after the participant stopped swaying. Stimulus presentation began with a 40-second baseline, during which a static field of 300 dots was displayed. Subsequently, four conditions were presented in random order: expanding optic flow, contracting optic flow, translational motion (either left-to-right or right-to-left, counterbalanced across participants), and static (repeating the initial static field of dots). For conditions involving motion, optic flow patterns were presented for the initial 20 seconds, followed by 20 seconds of static dots. During this static phase, the final frame of the optic flow phase was displayed statically for 20 seconds. This solution allowed us to explore whether participants exhibited more sway during the presentation of optic flow patterns or as an after-effect once the motion stopped abruptly. Since there was no significant difference in sway between the first and second halves of each condition, we analyzed the entire 40 seconds together.

*Statistical analyses*

 We considered the following standard parameters: ellipse area (as in Experiment 1), standard deviations (SD) along the anteroposterior and mediolateral directions (AP-SD and ML-SD, respectively), and the ratio between the latter two (cf. [54,57–59]). If participants experienced an illusion of self-motion induced by optic flow, we anticipated greater body sway along the axes corresponding to the perceived direction of movement. Specifically, we expected increased sway along the mediolateral (side-to-side) axis during the observation of translational motion. Similarly, we expected greater sway along the anteroposterior (front-to-back) axis when participants observed radial expanding and contracting optic flow. This would happen because expanding and contracting optic flow typically mimic forward or backward movement of the observer, respectively. Given that radial contracting and expanding optic flow patterns typically induce comparable sway along the anteroposterior axis, we averaged the log-transformed sway observed during the presentation of these patterns for each participant into an overall “radial” condition. To obtain a comprehensive measure of sway during the observation of static dots, as opposed to optic flow, we also averaged the two presentations of the static condition.

To explore potential differences in body sway among the different age-matched groups, we conducted a 3 x 3 mixed ANOVA, with the between-subjects factor group (Cataract-treated, Sighted, Blurred) and the within-subjects factor condition (static, radial, translational) for each parameter. Greenhouse–Geisser correction for sphericity assumption was used if necessary. Bonferroni-corrected pairwise comparisons were run whenever appropriate. To investigate body sway in the typical developing population (i.e., including all 42 participants aged 7 to 34 years, rather than only the 13 age-matched controls analyzed earlier) we conducted a repeated-measure ANOVA on log-transformed data, with the within-subjects factor condition (static, radial, translational) for each parameter. Further analyses were conducted to investigate the impact of age and height in the typical population. In the cataract-treated group, we extended these analyses to include time since surgery, age at surgery, and visual acuity.

**Results**

Table S3 provides group means and standard deviations for each parameter, condition and group (Cataract-treated, Sighted, and Blurred). Figure 2 shows the area of the 95% predicted sway ellipse for the CoP points for the three groups (upper panel) and the developmental sighted population (lower panel) under each condition, while a full overview of all parameters is reported in Figure S2. To better visualize the difference in body sway gain during optic flow relative to a static scene in cataract-treated participants compared to their age-matched controls, Figure 2 also displays the results normalized to the static condition (radial/static and translational/static) for each parameter.

*Comparison among cataract-treated, sighted, and blurred controls*

*Area*. The ANOVA revealed a main effect of group (F(2,35)=9.43, p<0.001). Pairwise comparisons showed that sway in cataract-treated participants was overall greater (36±2.9 cm2) than in both sighted (18.9±4.9 cm2, p<0.001) and blurred controls (18.5±2.5 cm2, p=0.003), while there was no significant difference between the two control groups (p=1). The main effect of condition was also significant (F(1.56,54.73)=6.82, p=0.004). The area in the static condition was significantly smaller than in both radial (p=0.011) and translational conditions (p=0.015). The condition x group interaction was not significant F(3.13,54.73)=2.58, p=0.06).

*AP-SD*. The analysis revealed a significant condition x group interaction (F(4,70)=2.76, p=0.035), with the sighted group showing larger values in the translational than in the static (p=0.022) conditions. The main effect of group was also significant (F(2,35)=3.60, p=0.038). AP-SD in cataract-treated participants was overall greater than in sighted controls (p=0.045). The blurred group exhibited intermediate results between the other two groups, not differing from either the cataract-treated (p=0.18) or the sighted (p=1) groups. The main effect of condition was not significant (F(2,70)=2.78, p=0.069) (Supplementary Figure S2, “AP-SD”).

*ML-SD*. The main effect of group was significant (F(2,35)=13.9, p<0.001). ML-SD in cataract-treated participants was overall greater than in sighted and blurred controls (both p<0.001). The two control groups did not statistically differ (p=1). The main effect of condition was also significant (F(2,70)=9.31, p<0.001), with the ML-SD being greater in the translational than in the static (p=0.005) and radial (p=0.024) conditions. The condition x group interaction was not significant (F(4,70)=1.19, p=0.32) (Figure S2, “ML-SD”).

*Ratio between SDs*. The analysis revealed a significant main effect of group (F(2,35)=7.45, p=0.002). The cataract-treated group differed from both sighted (p=0.028) and blurred (p=0.002) control groups, while the two control groups did not differ from each other (p=0.95). Specifically, participants in both control groups showed a greater ratio, indicating a more elongated shape of the ellipse along the anteroposterior axis (i.e., greater front-back sway) compared to cataract-treated individuals. The main effect of condition was also significant (F(2,70)=5.73, p=0.005), with a greater ratio in the radial than in the translational condition (p=0.014). The condition by group interaction was not significant (F(4,70)=0.45, p=0.77, Figure S2, “Ratio DSs”).

*Relation between performance and demographic variables*. To investigate whether any demographic variable (age at test, at surgery, time since surgery, spatial visual acuity, and height) influenced the performance of cataract-treated individuals, for each parameter and demographic variable we analyzed the data using Linear Mixed Models (LMMs), including condition (static, radial, translational), and each demographic variable, with and without potential interactions with condition, as fixed effects. All models included the random intercept as a random effect predictor. We used maximum-likelihood estimation to estimate the parameters. Age–at test and at surgery–and visual acuity were log-transformed to reduce skewness in their distribution and to linearize their relationships with the parameters. Age was the variable that most affected body sway. Given that age at test and at surgery were highly correlated (r=0.98, p<0.0001) and led to comparable results, we report here only results related to age at test. Age did not show significant interactions with condition. When considering age alone (i.e., without the interaction with condition), participants showed or tended to show less postural stability with age (e.g., main effect of age for SD-ML, t(35)=2.08, p=0.045). Previous studies in typically-sighted individuals have shown that body sway tends to decrease with age when participants are tested with eyes open (thus, while observing a static visual scene, [60]). In contrast, in cataract-treated participants, we found that body sway in the static condition increased with age (see regression models in Figure 2c). Figure 2c displays the linear regression model between visual acuity and the ratio of radial to static conditions for the SD-ML parameter. This suggests that individuals with higher visual acuity tend to be more sensitive to the influence of the specific optic flow pattern on postural control. No other effects of demographic variables on body sway were observed.

*Sensitivity to optic flow in the developmental sighted population*

Results on the sighted population are reported in detail in the Supplementary Material. Sway was usually greater in the optic flow conditions compared to the static conditions. Moreover, the translational condition usually induced larger sway than the radial condition. In contrast to our findings in cataract-treated participants, body sway in the static condition in the typically sighted population negatively correlated with age (Figure 2c, “Static”), indicating increased postural control during the observation of a static visual scene with age. Sensitivity to optic flow became more pronounced with age, as shown by the fact that the difference between static and translational conditions is more pronounced at an older age (Supplementary Material). An example of greater sensitivity to optic flow with age is provided in Figure 2c, which shows the positive relationship between age and the ratio between translational and static conditions.

**Discussion**

Experiment 2 revealed that the cataract-treated group exhibited greater body sway compared to both sighted control groups. Notably, this increased sway was evident already in the static condition, confirming the results of Experiment 1. Despite this overall increase in sway, cataract-treated participants showed less susceptibility to the influence of specific optic flow patterns. Indeed, when the condition x group interaction was significant, the effect was driven by the group of sighted controls tested in normal visual conditions, who displayed greater sway when exposed to optic flow patterns compared to the static condition. Visual acuity contributed to the different outcomes across groups, with body sway in blurred controls often intermediate between cataract-treated and typically-sighted individuals. The influence of visual acuity is further supported by cataract-treated participants with higher visual acuity demonstrating less sway along the mediolateral axis during radial expanding and contracting optic flow. This finding aligns with the expected impact of expanding and contracting optic flow, which primarily affects sway along the anteroposterior axis by eliciting an illusory sense of forward and backward motion, consequently inducing less mediolateral sway compared to the static condition. Thus, cataract-treated individuals with higher visual acuity may be more sensitive to the specific type of optic flow than those with lower visual acuity.

In the static condition, cataract-treated participants showed increased sway with age, unlike typically sighted participants [60,64]. While typically sighted individuals sway less overall with age, their sensitivity to optic flow increases, as evidenced by the widening disparity in sway between static and optic flow conditions with age. Even the youngest controls, aged 7-9 years, exhibit less sway overall while showing greater sensitivity to optic flow compared to the cataract-treated participants.

The translational optic flow appeared to have a stronger effect on sway than radial optic flow. This sometimes resulted in seemingly counterintuitive outcomes. Specifically, translational optic flow patterns not only induced greater sway along the mediolateral axis (i.e., greater ML-SD), as expected, but also greater sway along the anteroposterior axis (i.e., greater AP-SD), which is typically associated with radial optic flow. This result can be attributed to the overall larger sway area induced by the translational condition compared to the radial condition, which resulted in a higher standard deviation of CoP data along both sway axes (Figure 2b). However, when taking into consideration the ratio between the two axes of the fitted ellipse, it is possible to appreciate that radial optic flow induced a significantly greater ratio (i.e., a more elongated shape) along the anteroposterior axis than the translational optic flow did. Therefore, while both radial and translational optic flow patterns led to increased body sway compared to the static condition, with translational optic flow having a more pronounced effect, they exerted differential effects on body sway along the anteroposterior and mediolateral axes, as hypothesized.

**General Discussion**

When considering postural stability, Experiment 1 revealed that cataract-treated participants rely less on vision for stabilization than typically sighted controls, as shown by their smaller reduction in body sway when tested with eyes open compared to closed. Experiment 2 showed that in the typically developing population, the ability to use static visual input for stabilization increases with age. Previous studies have reported a similar reduction of postural sway with age in sighted individuals, stabilizing at adult-like levels by approximately age thirteen [60,64]. This improvement has been attributed to enhanced vestibular and visual contributions with age, along with better coordination across the senses [64,65]. Nonetheless, body sway with eyes closed consistently exceeds sway with eyes open regardless of age, highlighting the key contribution of visual input to postural stability [60,8,13,15]. Contrary to our findings in the typically developing population, we observed that cataract-treated participants increased their sway with age instead of decreasing it. Interestingly, in Experiment 1 we found reduced sway in participants tested further from surgery, suggesting increased reliance on vision for stabilization over time. Post-surgical visual and visuomotor experience, rather than maturational factors reflected by age, may play a role in this development.

When exposed to optic flow patterns, cataract-treated participants showed less sensitivity than sighted controls, despite exhibiting greater overall sway regardless of condition. Specifically, the difference in sway between observing static dots and optic flow is smaller in cataract-treated participants compared to sighted controls. This discrepancy is evident even when comparing cataract-treated participants to the youngest group of sighted participants, who already demonstrate less overall sway while displaying greater sensitivity to optic flow. Nonetheless, cataract-treated participants generally exhibited some sway trends similar to those of sighted controls, as shown by the significant main effect of condition for most parameters. Previous studies have demonstrated that typically developing infants are sensitive to optic flow patterns from birth [33,40,41]. However, the maturation of motion perception is a gradual process that extends over several years. Specifically, global motion sensitivity, which is mainly processed in area MT, takes longer to fully develop compared to local motion sensitivity, which is mainly processed in early visual areas [66,67]. Dynamic vision continues to develop throughout childhood, with adult-level performance being reached only around the age of 15 years [68] and sensitivity to optic flow still not fully developed by age 16 [48]. These findings suggest that the functions requiring the integration of input from lower-level processing areas take several years to mature. Congenital bilateral cataracts usually lead to deficits in global motion processing, with cataract-treated participants showing poorer coherence thresholds, reduced alpha oscillatory activity, and an absence of ERP modulation by visual motion coherence compared to typically sighted controls [47,49,69]. However, previous studies show that, despite poorer performance, cataract-treated participants can judge the global direction of dots, with some individuals exhibiting this ability even before surgery [70]. This finding indicates that a certain level of global motion perception can develop during early childhood despite the presence of cataracts. This may be attributed to the fact that information related to global motion can be extracted from very low spatial frequencies [71], which remain visible in participants with cataracts, sometimes even before surgical intervention, facilitating the perception of events even from highly blurred images. Still, visual acuity contributes to solving tasks requiring fine direction discrimination of fully coherent motion, as direction sensitivity correlates with visual acuity [70]. It is important to note, however, that we cannot quantify the contribution of pre-surgical residual vision in our sample. According to the WHO taxonomy, two participants had moderate visual impairment before surgery, and three had severe low vision. These residual visual abilities may have influenced post-surgery outcomes. Future studies with larger sample sizes and a broader range of pre-surgical residual vision will be crucial to further explore its potential contribution to the development of optic flow sensitivity. In our study, we observed that sensitivity to optic flow is influenced by visual acuity, with blurred controls demonstrating lower sensitivity compared to sighted controls tested under normal visual conditions. Additionally, there were indications that body sway in cataract-treated participants with higher visual acuity may be more affected by the specific type of optic flow compared to those with lower visual acuity.

Although visual blur affected performance, the difference between cataract-treated participants and controls cannot be solely attributed to blurred stimuli, as the overall sway of blurred controls was significantly lower than that of cataract-treated participants. Not only did cataract-treated participants display greater sway already in the static condition, but their sway pattern was characterized by greater variability across all directions. Specifically, the fitted ellipse to their CoP data was less elongated along the anteroposterior axis compared to controls, suggesting increased sway along the mediolateral direction as well. It has been suggested that, beyond cortical maturational processes [72], the onset of locomotion also contributes to the development of the ability to process optic flow [73]. Our findings suggest that the poorer pre-surgery experience with optic flow and its connection to self-generated mobility affected participants’ sensitivity to optic flow. Such a reduced sensitivity lasts after surgery, at least in the time frame we examined.

Although Experiment 1 suggests a possible improvement in the ability to utilize vision for stabilization over time, it is important to acknowledge that we had the opportunity to include only a relatively small number of participants, tested over a relatively short post-operative period. Unlike our previous studies in cataract-treated individuals [74–77,29], in the present study we have been unable to conduct follow-up tests with the same participants over time, due to the challenging circumstances posed by the political situation in Ethiopia and the COVID-19 pandemic. This has prevented us from tracking potential longitudinal changes within this cohort. A recent study on congenital cataract-treated individuals found worse postural control compared to controls even more than 10 years after surgery [15]. Despite using a different methodology (single-leg stance), it suggests early blindness may lead to long-term impairments in postural control. Further research is needed to determine if sensitivity to visual cues, like optic flow, improves over the years.

In summary, our study revealed that cataract-treated individuals demonstrate less ability than controls to use visual cues for stabilizing posture, together with a reduced sensitivity to optic flow, as measured in terms of its influence on posture. The use of vision for postural stabilization appears to partially develop with post-surgical experience.

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**Figure Legends**

**Figure 1. Experiment 1.** Left: Procedure. Postural stability was tested under two conditions: open and closed eyes. Body sway was assessed by determining the area of the 95% prediction ellipse of Center of Pressure (CoP) sway points for each participant and condition. Middle: Results. The median area is shown for each group (cataract-treated participants, in red, and sighted controls, in blue) and condition (open vs closed eyes, lighter and darker colour, respectively), while individual areas are shown in gray. While both groups significantly reduced body sway with open eyes compared to closed, the reduction was significantly smaller in cataract-treated participants than in controls. Right: Correlation between sway and time since surgery. Linear regression lines are presented for closed-eyes (y=83.7-26.6x, F(1,9)=8.45, p=0.017, R2=0.48) and open-eyes conditions (y=57.8-1.71x, F(1,9)=3.35, p=0.1, R2=0.27). Shaded areas indicated the 95% confidence intervals of the regression lines. The blue dashed lines indicate the median performance of the sighted participants, with closed and open eyes, shown for reference.

**Figure 2. Experiment 2.** A. Stimuli. Three conditions were shown: static (static field of dots), radial (expanding and contracting optic flow), and translational (left-to-right or right-to-left flow). B. Body sway parameters. The 95% predicted ellipse area, the standard deviation along the mediolateral (ML-SD) and anteroposterior (AP-SD) directions, and the ratio between these two measures were analyzed. Exemplary body sway responses to each condition in a typically sighted participant. C. Results. Upper panel: Sway in cataract-treated participants (N=13, red) and age-matched typically sighted controls, tested either in normal visual conditions (Sighted, N=13, blue) or with visual blur (Blurred, N=12, light blue). Back-transformed areas of the 95% prediction ellipse, averaged across participants in each group, are presented. Despite cataract-treated participants swaying significantly more than controls, their sway is less modulated by optic flow patterns. To highlight the impact of optic flow relative to a static scene, results normalized to the static condition (i.e., radial/static and translational/static) are displayed. Lower panel: body sway in the typically developing sighted population. Average sway is shown for the whole group (N=42, purple), the youngest participants (N=12, aged 7-9 years, light grey), adults (N=10, 21-34 years, dark grey), and the remaining sample (N=20, 10-16 years, grey). While younger participants sway more than older ones, they do so to a lesser degree than the cataract-treated group, while already showing greater sensitivity to optic flow. Error bars represent SEM. A series of linear regressions are shown for the cataract-treated participants and the whole group of sighted participants. In cataract-treated participants, the regression between age at test (log-transformed) and the area in the static condition indicates that sway increases with age (log(y)=6.24+0.75x, F(1,11)=5.26, p=0.04, R2=0.32). Conversely, in the typically-sighted population, sway in the static condition decreases with age (log(y)=8.29-8.48x, F(1,40)=4.55, p=0.039, R2=0.102), indicating better postural control with age. Moreover, while sighted participants show increasing sensitivity to optic flow with age, as exemplified here by the regression between age and the ratio between the translational and static conditions (log(y)=0.023+0.634x, F(1,40)=7.28, p=0.01, R2=0.15), in cataract-treated, linear regressions reveal no significant relationship between sensitivity to optic flow and either age (log(y)=1.53-0.19x, F(1,11)=0.23, p=0.64, R2=0.02) or time since surgery (TSS,y=1.072-0.004x, F(1,11)=0.001, p=0.98, R2=0.0001). The moderate relationship between visual acuity and the ratio of radial to static conditions for ML-SD (y=1.142-0.02, F(1,11)=3.39, p=0.09, R2=0.24) suggests that individuals with higher visual acuity tend to exhibit less mediolateral sway during the radial condition, thus greater sensitivity to optic flow. Shaded areas indicated the 95% confidence intervals of the regression lines.

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