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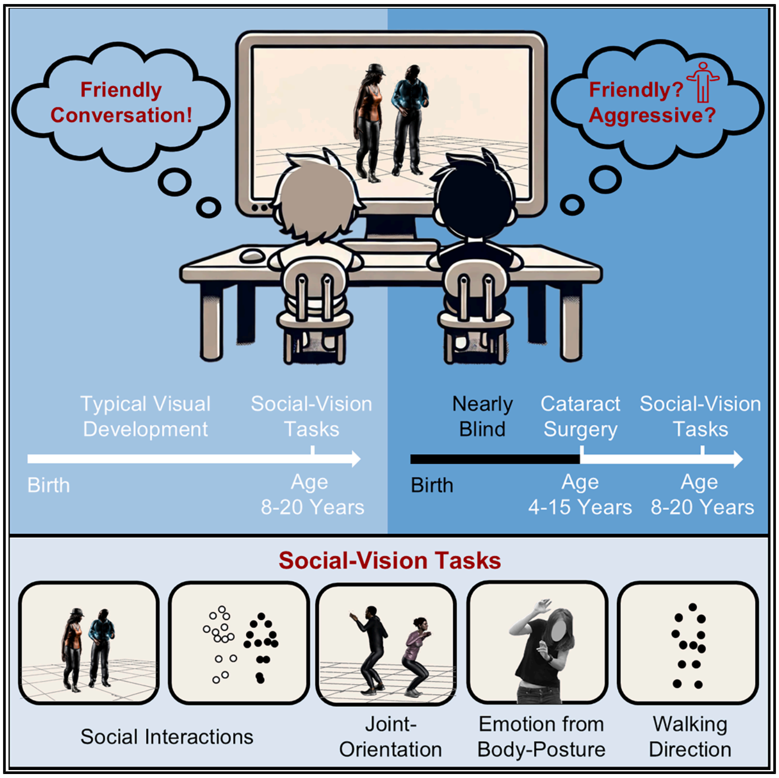
Expert-level understanding of social scenes requires early visual experience

Graphical abstract



Highlights

- Children born blind, regaining sight years later, were tested on social-vision tasks
- Recovery from early blindness is associated with poorer social scene understanding
- Recognizing body language and subtle biological-motion cues is also impaired
- Findings suggest a sensitive period for acquiring social-vision skills

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In brief

Social interaction; Social sciences

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Expert-level understanding of social scenes requires early visual experience

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SUMMARY

We studied 28 late-sighted Ethiopian children who were born with bilateral cataracts and remained nearly blind for years, recovering pattern-vision only in late childhood. This "natural experiment" offers a rare opportunity to assess the causal effect of early visual experience on later function acquisition. Here, we focus on vision-based understanding of human social interactions. The late-sighted were poorer than typically developing peers (albeit better than chance) in categorizing observed social scenes as friendly or aggressive, irrespective of the display format (i.e., full-body videos, still images, or point-light displays). This deficiency was maintained when retested later. They were also impaired in recognizing single-person attributes, which are useful for human interaction understanding (such as judging heading-direction based on biological-motion cues, or emotional states from body-posture gestures). Thus, the comprehension of visually observed socially relevant actions and body gestures is impaired in the late-sighted. We conclude that early visual experience is necessary for developing the skills required for utilizing visual cues for social scene understanding.

INTRODUCTION

Recognizing members of one's group, and deciphering their emotions and intentions, is important for survival in social animals (e.g., primates). Thus, it may not be surprising that rudimentary elements of social behavior may even be innate: Newborn infants show a preference for face-like patterns over nonface ones,[1,2] can imitate the oral gestures of others,[3] and are attracted by *biological* motion (compared to scrambled motion elements containing the same velocity pattern).[4] Basic social understanding follows soon: By six months infants effectively encode the goal object of others' reach, indicating that they have an understanding of goal-directed action.[5] They also assess individuals on the basis of their behavior toward others,[6] expect agents to minimize the cost of their actions,[7] and by the end of the first year of life they are able to follow others' gaze shifts.[8,9] Still, deep understanding of social content, based on subtle visual cues, is an acquired skill which is enhanced and refined throughout childhood, with some of the skills reaching adult-level only around 6–9 years of age.[10,11] This is mirrored by a slow maturation of the neural networks involved in social vision throughout childhood.[12]

Can such skills be acquired later in life, or is there a strict time window (critical period) for this learning? A study on macaque monkeys, reared without exposure to any faces (human or monkeys) for 6–24 months, provided important insights: A general preference for faces is apparently innate, but finer elements, such as greater sensitivity to faces from one's species, are dependent on the *initial* exposure to this face category, immediately following the deprivation period.[13] Early visual experience also plays a critical role in the development of expert face processing in *humans*. Evidence for this is based on a (relatively rare) natural experiment: Children born with dense cataracts in both eyes, precluding patterned vision until the lenses are removed and replaced with artificial ones through surgery, typically around 2–6 months from birth. These patients later develop normal looking preferences for face-like patterns,[14,15] and normal sensitivity to the shape of facial features[16] and to biological motion.[17] Nevertheless, they typically show long-lasting deficits in *configural* aspects of face processing, including holistic face processing[18] and sensitivity to the spacing of facial features.[19]

We study a similar group of Ethiopian children, born with dense bilateral cataracts. But in our case, due to a lack of proper medical care, the children were diagnosed and surgically treated (by our team) only years later. Before surgery, the patients had extremely limited vision: all had light perception, but most (19/28) did not have any pattern vision beyond 0.5 m (see individual details in the supplemental information, Table S1). After treatment, their visual acuity improved substantially, but was still far from normal vision (Figure S1) even years after surgery (replicating previous findings).[20–22]

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The patients' developmental track after surgery is not likely to follow that of infants, as they have developed a coherent representation of the world, including people's actions and motivations, through the other senses (e.g., via verbal and non-verbal communication). Nonetheless, their understanding of social cues in *visually presented* scenes may still be impaired. A recent study using point-light-displays (PLDs) showed that the categorization of another person's actions (e.g., jumping, running, dancing, and so forth) is intact in cataract-reversal patients.[23] On the other hand, we previously reported that these children typically have deficiencies in *following* the actions of others: For example, they often have impaired automatic imitation (in which observing an action prompts the compatible action).[24] They also fail to automatically follow the gaze of others (when indicated by eye position), despite acquiring sufficient resolution to extract eye position after surgery.[25]

The above were automatic actions, triggered by seeing others' actions. Here, we study the late-sighted' ability to *interpret and understand* social interactions. To that end, we presented the late-sighted children with videos and still images depicting social interactions between two people, asking them to categorize each interaction as "friendly" or "aggressive." Similarly aged control subjects could perform this task almost flawlessly, but the late-sighted (as a group) had significantly poorer performance, albeit better than chance. Further experiments revealed that they also show poorer sensitivity in discriminating more basic actions or features which are useful for social scene understanding (e.g., joint-orientation, walking direction, or body-posture implying specific emotions).

Together, our data suggest that social vision skills are impaired in the late-sighted, likely resulting from a more general, perceptual deficit (e.g., picking up subtle visual cues; or paying attention to multiple components in a face or a scene, and their *relational configuration*). These findings are consistent with a *sensitive period* for acquiring social vision skills.

RESULTS

We studied 28 Ethiopian children with early-onset dense bilateral cataracts, who were found and surgically treated by our group years later (ages 4–15). They were behaviorally tested between 4 months and 9.5 years after the operation (for the participants' ages at surgery and at test, see Table S1; for their individual performance levels, see Table S2). Our main goal was to assess their ability to use different visual cues, for interpreting the *social context* of observed scenes.

Discrimination of social interactions, based on motion and form (body-posture) information

Twenty-four late-sighted children participated in the first set of experiments (Figure 1). Each trial began with a short (silent) video or an image, depicting a prototypical human-interaction (between two avatar agents; e.g., talking, arguing, dancing; see Table S3 and Figure S3), followed by a report screen in which participants indicated whether the interaction was *friendly* or *aggressive*. Three separate experimental blocks were carried out, differing by the presentation format of the social interaction: (1) A full-body animation, (2) a characteristic snapshot from the animation, and (3) a Point Light Display (PLD) of the sequence.

The late-sighted had poorer image resolution than that of normally developing peers, despite their substantial improvement in visual acuity following surgery (Figure S1 and Table S1). To account for this limitation, which may well hamper performance, all *control* participants (30 Israeli and 16 Ethiopian) were shown a lowpass-filtered version of the original stimuli. Spatial frequencies above 1.5 cycles per degree (cpd) were filtered out, introducing image blur greater than that experienced by the late-sighted with the *poorest* visual acuity at the time of testing (Figure S1). Thus, under all our experimental conditions, the late-sighted actually had an *advantage* in image resolution in comparison to controls. Despite this, their group-averaged performance did not reach the expert-level of typically-developing peers (Figures 1D–1F), as corroborated by the statistical analysis: One-way ANOVA tests revealed a significant effect of group (Late-Sighted, Israeli Controls, Ethiopian Controls) on performance, in all three experimental conditions (*Full-Body Animation*: $F(2, 65) = 62.08$, $p < 0.001$, $\eta^2 = 0.66$. *Static-Snapshot*: $F(2, 67) = 25.46$, $p < 0.001$, $\eta^2 = 0.43$. *PLD*: $F(2, 66) = 32.77$, $p < 0.001$, $\eta^2 = 0.50$). Also, when using the Kruskal–Wallis nonparametric test (due to unequal variances across groups and non-normal residual distributions in some of the groups; see STAR Methods) these effects were still highly significant (all p's < 0.001; see STAR Methods for details). Post-hoc comparisons using Dunn's test with a Bonferroni correction for multiple comparisons, indicated that each of the control groups had significantly higher scores than the late-sighted group, in each of the tasks [*Full-Body Animation*, *Static-Snapshot*, *PLD*]: Ethiopian Controls: mean differences (in % correct) = [16.89, 18.32, 17.45], z = [3.70, 3.80, 3.23], p = [0.001, <0.001, 0.004], Δ = [0.79, 0.75, 0.65], where Δ represents Cliff's Delta, see STAR Methods; Israeli Controls: mean differences (in % correct) = [22.25, 20.52, 25.75], z = [6.24, 5.16, 5.75], all p's < 0.001, Δ = [0.94, 0.80, 0.89]. The performance of the Israeli controls was somewhat better than that of the Ethiopian controls (although not statistically different): mean differences (in % correct) = [5.35, 2.20, 8.31], z = [1.73, 0.60, 1.75], p = [0.251, 1., 0.239], Δ = [0.39, 0.14, 0.36]) in the three conditions. Thus, we cannot completely exclude the possibility that cultural differences or translation issues, might have had a small effect in social scene understanding, but the highly significant impaired performance of the late-sighted in comparison to their *Ethiopian* typically-developing peers clearly indicates that *early visual deprivation* hampers social scene understanding (for the scenes used in our test; see performance for each scene in Figure S2). Indeed, a majority of the late-sighted individuals did not perform significantly better than chance in the *Static-Snapshot* (16/24) and *PLD* (17/24) conditions. However, at the *group* level, the late-sighted were still significantly better than chance in all experimental conditions (*Full-Body Animation*: $t(22) = 12.28$, $p < 0.001$, Cohen's d = 2.56. *Static-Snapshot*: $t(23) = 6.31$, $p < 0.001$, Cohen's d = 1.29. *PLD*: $t(23) = 4.41$, $p < 0.001$, Cohen's d = 0.90).

Are these deficits mitigated with gained visual experience (following sight restoration), as in some tasks,[22] but not in others?[26] Since many of the late-sighted participants were

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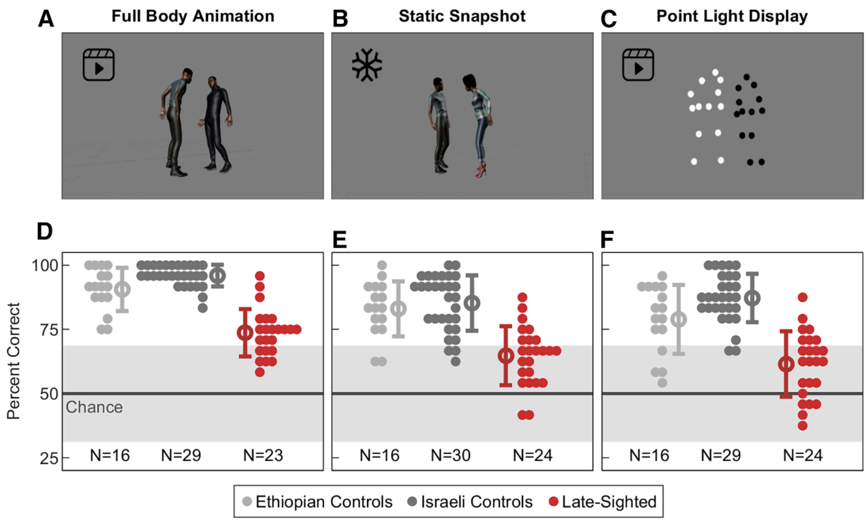

Figure 1. Discrimination of social interactions, based on motion and form (body posture) information

(A–C) Examples of the stimuli used in each format. The media icon indicates that we show here a single frame from the short video that was presented in the experiment, and the snowflake – that the stimulus was static. See Table S3, Figures S2 and S3 for the full set of stimuli and performance levels for each stimulus.

(D–F) mean (open circle), standard deviation (error bar), and distribution of the individual results (filled circles) of all participants in each task. The standard deviations allow the estimation of effect sizes (D: *Full-Body Animation*, E: *Static-Snapshots*, F: *Point Light Displays*). Light and darker gray: Ethiopian and Israeli control participants; Red: late-sighted. The horizontal black lines indicate chance level (50%), and the gray range – results that are not significantly above or below chance (at the individual-subject level; $p < 0.05$). Sample sizes of each group (N) are indicated at the bottom of each plot. See also Figure S4 for retest data.

tested years after surgery, and there was no evidence for better performance with time from surgery (see Table S4), this seemed unlikely. Still, to test this more rigorously, sixteen of the late-sighted participants were tested again 10 to 25 months following the initial test. Performance in this later test was similar to the initial test (Figure S4), and no significant differences were found between the two tests (*Full-Body Animation*: $t(15) = -0.46$, $p = 0.653$; *Static-Snapshot*: $t(15) = -1.59$, $p = 0.133$; *PLD*: $t(15) = 0.76$, $p = 0.460$).

The results in the first set of experiments are somewhat surprising, as previous literature indicated that late-treated cataract-reversal cases can recognize biological motion when embedded in noise,[17,27] as well as identify the type of action performed,[23] at a similar level as typically-developing peers. Thus, our naive expectation was that the cataract-treated cohort might be able to utilize *motion* cues as effectively as controls, when categorizing human social interactions. However, as mentioned above, the late-sighted were worse than controls when using either dynamic motion videos or static images. To further explore potential bottlenecks, which may impede the late-sighted' performance in this rather complex social task, we designed three additional tasks – each focused on a different component – which are all useful for understanding social interactions: (1) assessment of the joint-orientation of actors in the scene ("*Facingness*"[28]); (2) sensitivity to *fine* differences in biological motion, and (3) understanding the *emotion of each individual* in the scene, based on body-posture.

Discrimination of joint-orientation

For assessing participants' ability to judge the joint orientation of the agents in the scene, 18 late-sighted and 27 Israeli control participants were tested on a *joint orientation* discrimination task. Participants viewed short videos or images similar to those presented in the above *Social-Interactions* tasks, in their original configuration and in a "facing away" configuration (with mirrored actor-orientations; see examples in Figure 2A). Participants then indicated the avatars' joint orientation, i.e., whether they were facing each other or in opposite directions. Two separate experimental blocks were carried out, differing by the presentation format of the social interaction: (1) A full-body animation, and (2) a characteristic snapshot from the animation. As in the *Social-Interactions* tasks, control subjects were shown blurred stimuli, matching the poorest acuity of the late-sighted participants. We expected that, despite the relative simplicity of this task, the requirement to take into account *joint* aspects of two actors may lead to a deficiency in the late-sighted' performance.

In accordance with this being a more basic task, all late-sighted participants achieved above-chance performance in

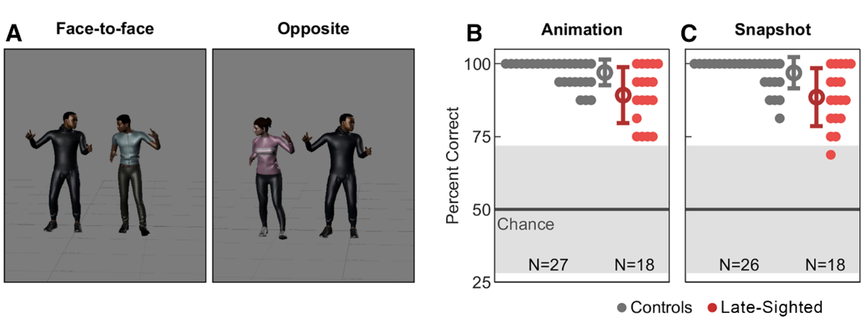

Figure 2. Discrimination of joint-orientation

(A) Examples of the stimuli used in this task (participants judged if the two avatars were facing each other or in opposite directions). For the *Animation* block, these are single frames from the short videos that were presented in the experiment.

(B and C) mean (open circle), standard deviation (error bar), and distribution of the individual results (filled circles) of all participants in each task (B: *Full-Body Animation*, C: *Static-Snapshot*). Colors and markings of the chance range are as in Figures 1D–1F.

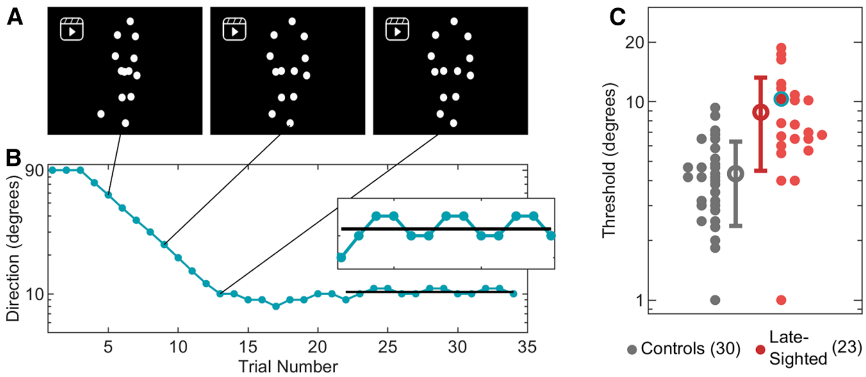

Figure 3. Sensitivity to biological-motion (BM) walking direction

(A) Single frames of the point-light displays (of a person walking rightward at angles of 58, 24, and 10°) that were presented in the experiment.

(B) The staircase procedure of an exemplary late-sighted participant. The threshold walking direction (black horizontal line) was assessed from the last 6 reversals, which are magnified in the inset. The threshold of this exemplary subject was 10.3°.

(C) Distribution of the individual thresholds (gray: controls, red: late-sighted; The subject whose staircase is shown in B is marked by a cyan outer-frame). Group averages and standard deviation (STD) are also shown (Large open circles and error bars; the STD error-bar size below and above the average is asymmetric due to the log-scale of the y axis). Group sample sizes are depicted in parentheses.

the *Full-Body Animation* block, and 17/18 in the *Static-Snapshot* block (Figures 2B and 2C). Nonetheless, and despite what seems to be a ceiling effect in the control group (Figures 2B and 2C), the late-sighted were still significantly poorer than controls in both experimental blocks (*Full-Body Animation*: $t(22) = 3.23$, $p = 0.004$, Cohen's d = 1.05. *Static-Snapshot*: $t(24) = 3.26$, $p = 0.003$, Cohen's d = 1.05; degrees of freedom were adjusted to account for unequal variances in the two groups. The results were also confirmed using the nonparametric Mann-Whitney U test, due to the non-normality of the distributions; see STAR Methods). Thus, we conclude that the late-sighted are somewhat impaired even in a simple task, which may well serve social situation understanding, requiring the discrimination of the joint orientation of the two actors.

Sensitivity to biological motion (BM) walking direction

We assessed the participants' ability to perform fine discriminations using biological motion (BM) stimuli. Our working hypothesis was that although the late-sighted can all *recognize* biological motion, they may well be impaired in assessing the *exact* direction of motion (which can provide a clue for social situation understanding). To that end, a subset of 23 late-sighted participants, and a new group of 30 Israeli typically-developing control participants indicated the direction of walking (left/right) of a human figure, depicted by point-light video displays (Figure 3A). The initial walking direction was +/− 90° with respect to *straight ahead* (i.e., 0°), and varied following a staircase procedure until the threshold was assessed (see STAR Methods and Figure 3B). Control subjects were shown blurred videos, matching the poorest acuity of the late-sighted participants, as in the *Social-Interactions* tasks. Figure 3C depicts the distribution of the thresholds in the *Walking Direction* task, in the late-sighted group and controls. The late-sighted could clearly perform the task successfully when the left and right walking directions were very different (see example case, Figure 3B), but were worse than controls when required to note *subtle* differences in walking directions. This is reflected in the threshold (Mean thresholds: Controls = 4.34, Late-Sighted = 8.86°) which is significantly higher in the late-sighted group ($t(29) = 4.60$, $p < 0.001$, Cohen's d = 1.33; degrees of freedom were adjusted to account for unequal variances in the two groups, see STAR Methods). We conclude that while the recognition and interpretation of biological motion is possible following operation, the late-sighted are still hampered in their ability to assess *precise* walking direction, from biological motion cues.

Discrimination of emotions from still images of body-postures

We applied a similar simplification strategy to the still images: If the hampered performance of the late-sighted group in the recognition of human *interactions* is partly due to their impaired capability to interpret *body posture* cues, this should be evident even when the actors are *not* interacting with one another. To that end, we had participants (Late-Sighted: $N = 21$, Controls: 29 Israeli, 12 Ethiopian), judge the emotion of a *single* actor (presented on a computer screen), standing in a position which conveys either anger or fear (Figure 4A). The distributions of individuals' performance from the three groups are shown in Figure 4B. A one-way ANOVA revealed a significant effect of group (Late-Sighted, Israeli Controls, Ethiopian Controls) on performance ($F(2, 59) = 18.49$, $p < 0.001$, $\eta^2 = 0.39$), also corroborated by the Kruskal–Wallis nonparametric test ($p < 0.001$; see STAR Methods). Post-hoc comparisons using the nonparametric Dunn's test with a Bonferroni correction for multiple comparisons, indicated that both groups of controls had significantly higher scores than the late-sighted group (Ethiopian Controls: mean difference (in % correct) = 18.69, $z = 3.65$, $p < 0.001$, $\Delta = 0.66$. Israeli Controls: mean difference = 19.41, $z = 4.21$, $p < 0.001$, $\Delta = 0.73$), with no significant effect between the two control groups (mean difference = 0.72, z = 0.33, $p = 1.$, $\Delta = 0.13$). As in the *Social-Interactions* tasks, the late-sighted group's performance in the body-posture discrimination task was significantly above chance ($t(20) = 6.13$, $p < 0.001$, Cohen's d = 1.34). We conclude that the late-sighted are, on average, poorer than typically- developing peers in assessing emotion based on body posture cues.

DISCUSSION

Collectively, our results suggest that social vision is compromised if one suffered from prolonged early-onset visual deprivation in

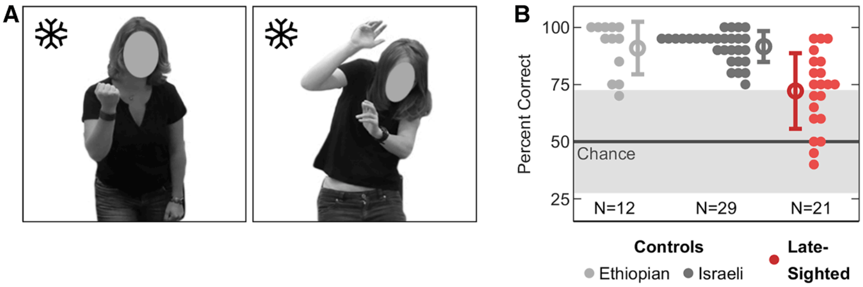

Figure 4. Discrimination of emotions from still images of body postures

(A) Examples of the stimuli used, depicting "angry" and "fearful" body postures. The face was masked by an ellipse to annul the use of facial gestures. The snowflake icon indicates that a single image was shown (rather than a video). See Figure S3 for the full set of stimuli and performance levels for each stimulus.

(B) distributions depicting the percent of correct judgments between "angry" vs. "fearful" images, for each group. Colors, group averages, STDs, and chance range markings are as in Figures 1D–1F.

early childhood, during which social vision typically develops.[29] It is important to note that control participants were able to recognize the social scenes, despite imposing a blur equivalent or worse than that experienced by the late-sighted. Thus, high-resolution input during childhood may be important for *acquiring* some of the skills required for social vision, but it is *not* crucial for *extracting* this information (at least in our tests), if one has had prolonged experience with high-resolution visual input during normal development.

Previous studies demonstrated that some socially related visual tasks are susceptible to a relatively short *sensitive period*, while others can be learnt later in childhood, despite early visual deprivation. For example, telling a face from a non-face can be acquired by the late-sighted rather quickly, reaching normal performance within ~6 months from sight retrieval.[30] Biological-motion (BM) perception provides another example of a capability that can be recovered after early visual deprivation, but not to its full extent. BM *recognition* may even be innate, as it is present in rudimentary form immediately at birth[31] as well as at the first instance of sight recovery in the late-sighted.[32] Sight-recovery children can also identify BM in the presence of noise, at a level similar to that of controls[17,27] and are able to identify distinct action categories from BM stimuli (e.g., running, jumping, and so forth) as good as typically-developing peers.[23] However, these are all relatively *crude* judgements. Here, we provide clear evidence that the late-sighted are *impaired* when the *fine* assessment of the direction of biological motion is required. A similar limitation is encountered by the late-sighted, when tested with more complex face-related tasks than mere face/non face discrimination: identification of *specific* faces, and holistic face processing, requiring the integration of subtle cues, is severely hampered throughout life even if the early deprivation period was very short (2–12 months).[18,33] This finding may have its neural correlates: congenital cataract-treated cases typically have an abnormal N170, an event related potential (ERP) assumed to reflect the structural encoding of faces,[14,34] and show reduced activation and impaired functional connectivity within the face network.[35]

Recently, we found that the late-sighted do not follow the eye-gaze of others even years after surgery and despite attaining sufficient visual acuity.[25] Mapping someone's gaze direction to a specific position in space is a difficult computational problem, but it can be learnt by registering the head and eye position during an *object-grasping hand action*, which serves as a pointer in space.[36] Still, this requires attending and encoding of multiple (and rather fine) elements in the scene and associating their co-occurrence, which may be impossible for the late-sighted. Thus, accumulating evidence suggests that following prolonged early-onset visual deprivation, tasks requiring the registration and integration of *subtle* visual cues are not fully recovered. The data presented here, indicating *impaired understanding of social scenes*, may well be the result of such *general* difficulties, rather than a specific deficiency in *social* situation understanding per se.

We further examined the extent to which *specific* elements in the scene, which are useful for social interpretation, can be understood by the late-sighted children. The assessment of other people's emotions is based on body posture features and movement patterns of the actor. It was recently shown, using both behavioral methods and computational modeling, that multiple *postural* features (e.g., limb angles and symmetry) are relevant for understanding others' emotions. In addition, kinematic factors such as the *directionality* of the movement, were found to be critical for the recognition of fear and anger.[37] Here, we tested the late-sighted' ability to judge the exact direction of an agent's motion, actors' joint heading-orientation, and postural features. They were impaired in all these aspects, and each factor may hinder understanding of social scenes.

We speculate that on top of this deficiency in assessing separate features, the requirement to attend and register *multiple components* may further amplify the late-sighted' problems in assessing social scenes. Social situation understanding requires attention to, and integration of information from multiple sources, especially when assessing social *interactions*, in which the *relational configuration* between actors is often of key importance. Consider an image in which two people are seen hugging. Whether the hug is an affectionate one or a formal one, depends on fine subtleties, such as the exact location of the hugging hands on the hugged body, the distance between the two actors, mutual head orientation, and other refined body-language signals (See Figure 13C, in Ben Yosef, Assif & Ullman 2018).[38] Similarly, a scene in which two actors are raising their hands might be understood as an aggressive interaction rather than play (e.g., imitation, dance), depending on the exact body configuration of the actors and the synchrony of action between them. Our data underscores consistent misinterpretations of *joint* aspects of actors' interactions, as well as difficulties in discerning the emotional cues conveyed through the body postures of *individual* actors, thus demonstrating a high-level behaviorally relevant effect of early visual deprivation. Recent findings suggest that there is a specialized cortical pathway for visual social interaction perception, organized in a hierarchical fashion (including the lateral occipitotemporal cortex (LOTC), extrastriate body area (EBA), and posterior superior temporal sulcus (pSTS)[28]. If this is indeed the case, our data showing the late-sighted impairment in social vision understanding may suggest that the late-sighted would show an abnormal pattern of activity in these cortical regions. We hypothesize that abnormal activity should be found already in the lower tiers (LOTC/EBA), which are putatively involved in the extraction of the basic primitives (i.e., building blocks) of social scenes. This remains to be seen.

Limitations of the study

It is important to compare the behavioral results of the late-sighted to those of other patient groups, which we lack here. These include (i) early-treated cataract cases (which are typically operated within 6 months from birth) and (ii) developmental cataract cases, in which vision loss occurred later in childhood (to assess the importance of *early* visual experience vs. later in childhood)[14,34]; The late-sighted, having had a longer, early-onset deprivation period, are expected to have greater visual deficiencies, as is indeed typically the case.[25] The lack of correlation between the subjects' age at operation and their success in the social tasks (Table S4) may suggest that the sensitive time-window for this fine skill-acquisition ends before the age of the youngest-operated patient, i.e., 4 years. However, this is far from conclusive evidence, as only two of the patients were operated on before the age of 8 (Table S1).

Another important control group we currently lack is (iii) people with congenital nystagmus (unrelated to cataract), to allow the assessment of uncontrolled jerky eye movements (which are always present in the late-sighted) on behavioral performance.[39] Vision, after all, is *active*, utilizing eye movements to *explore* the world. Thus, nystagmus per-se, may impair behavioral performance. This important factor has generally been ignored until recently.[39,40] It certainly merits further research.

In addition, we did not have typically-developing *Ethiopian* children in the *Joint-Orientation* and *BM Walking-Direction* experiments. Subject recruitment in Ethiopia, specifically of children (around the ages of the late-sighted group), is challenging. We therefore had to prioritize, and chose to collect sufficient data for the tasks we believed to be more susceptible to cultural differences or translation issues, namely the *Social-Interactions* and *Body-Posture* tasks. We are quite confident that the late-sighted fully understood the *Joint-Orientation* task, given that the experiment was only initiated if the participants performed flawlessly on exemplar stimuli presented to acquaint them with the task requirements, and that their individual performance levels were all significantly better than chance; Translation was not an issue in the BM Walking-Direction task since in all cases, the *staircase* procedure converged to thresholds better than the initial heading directions (+/−90 deg).

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Ehud Zohary (udiz@mail.huji.ac.il).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Experimental results of the late-sighted participants reported in this article are available in Table S2. Additional raw data, as well as the standard custom-built MATLAB scripts used in this study, will be shared by the lead contact upon request.
- The stimuli datasets used in this article have been deposited in a public repository and are available as of the date of publication at Mendeley Data: https://doi.org/10.17632/m448rzky7y.1.
- Any additional information required to reanalyze the data reported in this article is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization, I.N., S.A., A.Y.S. and E.Z.; methodology, I.N., S.A., A.Y.S. and I.B.-Z.; investigation, I.N., S.A., A.Y.S., I.B.-Z. and E.Z.; formal analysis, I.N., S.A. and A.Y.S.; software, I.N.; visualization, I.N.; writing—original draft, I.N. and E.Z.; writing—review and editing, I.N. and E.Z.; funding acquisition, E.Z.; project administration, I.B.-Z. and E.Z.; supervision, E.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
  - Participants
- METHOD DETAILS
  - Apparatus and stimuli
  - Translation procedures
  - Visual Acuity Assessment
  - Image Blur Control
  - Social-interactions task
  - Joint-orientation task
  - BM walking-direction task
  - Body-Posture Emotion Discrimination task
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Performance metrics
  - Inclusion Criteria and Tests
  - Outlier removal
  - Handling variance and non-normal residuals

SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Social Stimuli (videos, images)	This paper	https://doi.org/10.17632/m448rzky7y.1
Software and algorithms		
MATLAB	MathWorks	https://www.mathworks.com
SPSS	IBM	https://www.ibm.com/spss
Experiment Builder	SR Research	https://www.sr-research.com/software
Motion Builder	Autodesk	https://www.autodesk.com
Other		
Motion capture data	Carnegie Mellon University Motion Capture Database	mocap.cs.cmu.edu
Motion capture data	Motek Entertainment	motekentertainment.com
Motion capture data	PLAViMoP Bidet-Ildei et al.[41]	https://plavimop.prd.fr/index.php/en/motions
Avatars	Mixamo	https://www.mixamo.com
Body-posture images	Bochum Emotional Stimulus Set Thoma et al.[42]	https://www.ruhr-uni-bochum.de/neuropsy/BESST.html

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Participants

Twenty-eight Ethiopian children with early-onset bilateral cataracts (17 girls; ages 8.4 – 20.4 years, mean age = 14.2 years, STD = 3.2) met our inclusion criteria (see inclusion criteria and tests below) and participated in the experiments. Different subsets participated in the specific tasks, according to their availability at the time of testing: 24 participated in the first session of the *Social-Interaction* tasks (14 girls; mean age = 14.0, STD = 3.0); 16 in the second session (10 girls; mean age = 14.9, STD = 3.3); 18 in the *Joint-Orientation* task (12 girls; mean age = 14.1, STD = 3.2); 23 in the *BM Walking-Direction* task (13 girls; mean age = 13.9, STD = 3.2), and 21 in the *Body-Posture* task (14 girls; mean age = 14.4, STD = 3.4).

Separate groups of typically-developing participants served as control groups for the different tasks: *Social-Interactions*: 30 Israeli (15 girls; mean age = 12.0, STD = 2.2) and 16 Ethiopian (all boys; mean age = 12.9, STD = 3.4); *Joint-Orientation*: 27 Israeli (15 girls; mean age = 12.0, STD = 2.3); *BM Walking-Direction*: 30 Israeli (18 girls; mean age = 11.2, STD = 2.1); *Body-Posture*: 29 Israeli (13 girls; mean age = 10.81, STD = 2.2) and 12 Ethiopian (1 girl; mean age = 12.8, STD = 3.6). All control participants had normal or corrected vision, as reported by their guardians.

The late-sighted participants' dense bilateral cataracts were most likely congenital or developed within three months after birth, as all had clear nystagmus, a classical sign of early-onset blindness.[43] All of them attend (or attended in the past) blind schools, and acquired basic reading skills via Braille. Pre-surgical ophthalmological examination showed that they had extremely poor pattern vision: typically, limited to light or hand motion perception and, at most, finger counting from close range. We assessed the pre-operation ("pre-op") visual acuity (in terms of the cutoff spatial frequency, measured in *cycles per degree*; cpd) of 24 (out of 28) participants, using our tests developed for children with severe visual disabilities (see visual acuity assessment below and McKyton et al.[44] for the tests' details). The acuity scores were also converted to log of minimum angle of resolution (logMAR[45]) for better comparison with other studies (Table S1). The patients' average pre-op logMAR was 1.6 (corresponding to a geometric average of pre-op spatial frequency of 0.76 cpd). All had acuity worse than 6/60 (i.e., < 3 cpd; logMAR > 1; the standard definition of legal blindness in the U.S.) indicating a *severe vision impairment* by the standards of the World Health Organization (WHO).[46] 15/24 had acuity worse than 3/60 on the Snellen scale (< 1.5 cpd; logMAR > 1.3), i.e., *blind* by WHO standards. Lack of earlier diagnosis and/or local resources/facilities prevented these children from receiving early treatment. They were diagnosed by our team through an active screening effort, and consequently had cataract surgery (removal of the opaque lenses and implantation of artificial intraocular lenses) in both eyes at late childhood (ages 4 – 15.2, mean age = 10.2 years, STD = 2.8) at Hawassa Referral Hospital. Visual acuity typically improved substantially following surgery, but the magnitude of improvement varied among patients (Figure S1). The children performed the tests (in Hawassa Referral Hospital or in the Shashemene / Sebeta blind schools) 4 months to 9.5 years after the operation. Only patients whose post-operation ("post-op") acuity was better than 3/60 at the time of testing (> 1.5 cpd, equivalent to logMAR < 1.3) were included in this study. As for the first testing session (after operation), 9 of them still had *severe vision impairment* (according to the WHO categorization[46]; acuity < 3 cpd); 16 had *moderate vision impairment* (< 10 cpd); 2 had *mild vision impairment* (< 15 cpd), and only one reached the highest value measurable in our tests, thus possibly indicating close to normal vision. The children's visual acuity typically improved to some extent by the later testing sessions, but only rarely did they reach close to normal vision (for the full details, see Table S1).

The children's guardians gave their written consent for the operation and for participating in the behavioral tests. The procedures were approved by the ethics committee of the Hebrew University of Jerusalem and Hawassa University.

METHOD DETAILS

Apparatus and stimuli

We used a 15'' laptop computer with a touch screen (resolution: 1920 X 1080 pixels).

The late-sighted participants were seated 40 cm from the screen, but were allowed to move a bit closer or further away according to their preference. Individuals' distances were measured in each test session (see Table S1). The control participants were seated 40 cm from the screen, and were allowed to move a bit further away (to ensure a viewing distance of at least 40 cm).

In all experiments, stimuli were presented and responses were recorded using Experiment Builder software (SR Research, Ottawa, Ontario, Canada).

Translation procedures

In each experimental session conducted in Ethiopia, the Israeli experimenters were accompanied by local bilingual translators. Prior to testing, the experimenters briefed the translators in English on each task. The translators then conveyed these instructions to the participants in either Amharic or Oromo, according to the child's language preference. Throughout the experiment, both the Israeli experimenter and the local translator were present to ensure the participant fully understood the task.

Visual Acuity Assessment

Visual acuity of the late-sighted participants was individually assessed before and after operation using the contrast sensitivity function (CSF). Participants saw gratings of specific spatial frequencies at various contrast levels and were asked to report the grating orientation (horizontal or vertical) on each trial. Their performance was used to adaptively change the contrast using a staircase procedure and thereby assess the contrast threshold for each spatial frequency. Plotting the contrast threshold as a function of the spatial frequency yielded the CSF of the participant (Figure S5). The cutoff frequency – the highest frequency that can still be seen by the viewer (using the maximal contrast), was assessed by fitting the CSF with the truncated log-parabola form.[47] For further information about the CSF experiment, see McKyton et al.[24] When the CSF test (based on the orientation discrimination task) was impossible/failed, it was replaced by a simpler detection test. In this test, a large white circle was shown on a black background, at varying spatial positions. Participants were asked to detect and touch the circle. Its size was adaptively changed using a staircase procedure to assess the threshold circle size for detection. When possible, the circle was replaced by a two-cycle Gabor patch (at full contrast), whose size and position was changed using the same staircase procedure, to assess the highest possible spatial frequency, at which detection was still possible. This was used as an estimation of the cutoff frequency. Irrespective of the assessment procedure, the cutoff spatial frequency was converted to visual degrees (i.e. cycles per degree; cpd) given *each individual's viewing distance*, which was measured per participant each test session. The distribution of all pre- and post-op cutoff frequencies is plotted in Figure S1A. Note that in the vast majority of cases, surgery led to improved visual acuity. Still, in 8/24 (33%) late-sighted participants, post-operative acuity was above 1.5 cpd (i.e. our inclusion criterion), but did not surpass the criterion of legal blindness (< 3 cpd). However, post-op visual acuity had little to do with performance in the social interaction tasks: the performance of patients whose post-op acuity remained below the threshold of legal blindness (< 3 cpd) was no different than that of the ones who were no longer legally blind (> 3 cpd; See Figures S1C–S1E).

Visual acuity of the control participants was normal or corrected, as reported by their guardians.

Image Blur Control

We assessed the cutoff spatial frequency of each of the late-sighted participants (in each test session, see Table S1 and visual acuity assessment for further details), and included in the study only participants whose acuity at test exceeded 1.5 cpd (as detailed in inclusion criteria and tests below). To ensure that differences between the cataract-treated and control groups were not due to the late-sighted individuals' blurry vision, the control participants were tested using low-pass filtered versions of all the stimuli, eliminating visible spatial frequencies above 1.5 cpd (assuming a viewing distance of 40 cm; Figure S1) This was done by convolving each movie frame in the videos, as well as each image in the static conditions, with a 2D Gaussian blur kernel ($\sigma(x) = 13$ pixels i.e., 0.3^{o} at 40 cm viewing distance, in both dimensions). After this, the power at 1.5 cpd (our chosen cutoff frequency) is 5% of its original power. Accordingly, control participants were seated at least 40 cm from the screen (if they preferred, they could sit further away), to ensure spatial frequencies above 1.5 cpd are not available for them. For more details about the filtering procedure, see Orlov et al.[22]

Social-interactions task

Twenty-four late-sighted and 46 Control participants (30 Israeli, 16 Ethiopian) completed the *Social-Interactions* experiments (Figure 1). Sixteen of the late-sighted participants were tested again on the same tasks after 10-25 months from the initial test (Figure S4).

Twelve short (1.9-2.9 seconds) sequences of motion capture stimuli were used, conveying human interactions between two agents (e.g. talking, arguing, dancing, etc.). Selection of the social interaction sequences was based on the following guiding rules: (1) Each video portrays an interaction that could trivially be classified as "friendly" or "aggressive" by the experimenter; (2) For each exemplar, the nature of social interaction is conveyed clearly, independent of display format (full video, a static snapshot taken from the video, or Point-Light-Display). The chosen interactions are described in Table S3. Stimuli sizes differed slightly between scenes and presentation formats. Each avatar / point-light figure was about 10 X 4 cm on the screen, corresponding to 14.3 X 5.7 visual degrees, at a 40 cm distance from the screen. The dots comprising the point-light stimulus had diameter of 0.8 cm, i.e. 1.1 visual degrees.

Each trial began with a 300 ms presentation of a fixation point in the screen center, after which a social-interaction scene was presented – either until the video ended (1.9-2.9 seconds, depending on the specific scene), or, in the *static-snapshot* trials (see below), after two seconds. Following scene presentation, a report screen appeared, in which a smiling emoji appeared on the right and an angry one on the left. Subjects indicated whether the interaction was friendly or aggressive, by touching the touch screen at the appropriate position (friendly: right; aggressive: left). In some cases, participants preferred to report their answer verbally. In these cases, the experimenter touched the screen according to the participant's report. Report time was not limited and subjects were not encouraged to answer quickly. Following report, an *Inter-Trial Interval* (ITI) screen appeared, with a dot at the bottom-center. The next trial was triggered by the subject pressing either the dot on the screen or the space bar on the keyboard.

Three experimental blocks were carried out, differing by the presentation-format of the stimuli: (1) full-body animation, (2) a static snapshot from the animation, and (3) a Point-Light-Display (PLD) of the sequence. For each format, two versions of the same interaction were created, differing by point of view, and the identity of the animated avatars.

To avoid potential priming effects from the full video to the impoverished (PLD and static) formats, the full-animation experiment was always presented last, and the order of the PLD and static experiments was counterbalanced between subjects. Trial order within each experiment were randomized. To further minimize potential priming, we maximized the variation between the stimuli: different combinations of six "agents" (avatars) were used for different trials, and points of view of the scenes were also varied. To avoid potential learning of the correct answer for each stimulus (which was repeated in different variations throughout the experiments), no feedback was provided during the task. In each experiment, 2 versions of 12 interactions (6 "friendly" and 6 "aggressive") were presented, resulting in an overall trial count of 12 interaction-scenes X 2 versions = 24 trials in *each* of the three experiments. Experiment duration varied considerably between participants, since there was no requirement to perform the task quickly (our emphasis when explaining the task was on accuracy rather than speed). Moreover, in the cases the experimenter touched the screen instead of the participant, each trial was further extended. Mostly, participants finished the three experimental blocks (including instructions and examples) within 10-15 minutes.

The motion capture data (i.e. PLDs) were obtained from three databases: MOCAP: mocap.cs.cmu.edu, created with funding from NSF EIA-0196217; Motek: motekentertainment.com; and the PLAViMoP database[41]: https://plavimop.prd.fr/index.php/en/motions.

The animated videos were created using the Autodesk MotionBuilder software: http://usa.autodesk.com, with different combinations of six avatars (3 male), downloaded from the Mixamo dataset: https://www.mixamo.com.

Joint-orientation task

Eighteen of the late-sighted and 27 control participants viewed 8 videos or images conveying human interactions (5 of the scenes used in the *Social* task, and 3 novel scenes, with similarly-sized figures), once in the original configuration and once with mirrored actor-orientations (see examples in Figure 2), for a total of 16 trials, presented in random order. Two blocks were used – one with full-animations of the scenes, and one with static-snapshots. Trial structure was the same as in the Social-Interactions experiment, except that participants reported the avatars' joint orientation, i.e. whether they were facing each other or in opposite directions (rather than the social nature of the scene) – by touching corresponding arrow icons (arrows facing each-other on the right, and opposite arrows on the left). Since each stimulus was presented twice (once in each configuration), no feedback was provided, to prevent participants from deducing the answer for the second repetition. As in the Social-Interactions experiment, speedy performance was not encouraged and there was variability in the duration of the experiment. Most participants finished the two blocks within 7-10 minutes.

This experiment was carried out only for participants who had already finished the Social-Interactions experiment (either on the same day or in a separate session), to avoid potential priming effects from the common stimuli between the two experiments (e.g. from the full-body animation of a specific scene to the impoverished versions).

BM walking-direction task

Twenty-three late-sighted and 30 Israeli control participants completed the BM Walking-Direction experiment (Figure 3).

For this experiment, a motion capture sequence conveying a walking person was utilized for creating PLDs of all walking directions (at 1-degree resolution): between 90 degrees leftward to 90 degrees rightward (relative to the "straight-ahead" walking direction).

The PLD was made of 13 dots, each with diameter 0.5 cm on the screen, corresponding to 0.7 visual degrees at 40 cm distance. The overall point-light figure was 8.5 X 2.5 cm, i.e. 12.1 X 3.6 visual degrees.

Each trial began with a 300 ms presentation of a fixation point in the screen center, after which a PLD video of a walking person appeared at the screen center. On the same screen, two arrows were shown – a leftward arrow on the left and a rightward arrow on the right. Subjects indicated the walking direction of the point-light figure, by pressing the appropriate arrow on the touch screen. The BM video was played continuously (in a loop) until the subject's report. Report time was not limited, and subjects were not encouraged to answer quickly. Following a correct response, a brief (400 ms) sound was played as feedback. Following wrong responses, no feedback was given. In either case, after 400 ms, an ITI screen appeared, with a dot at the bottom-center. The next trial was triggered by the subject pressing either the dot on the screen or the spacebar on the keyboard. Each session started with the easiest walking direction to be discriminated, i.e. 90° right (+90°) vs. 90° left (-90°). To assess each participant's discrimination threshold, the walking direction angle was changed adaptively (towards the straight-ahead direction: 0°) using a staircase procedure. To facilitate convergence, the initial trials followed a 'one-down, one-up' rule (excluding the two first mistakes, which were ignored). The staircase step size was 20% of the current angle after a correct answer, and 25% after a wrong one (to retain symmetry, e.g., after a mistake in a 72° trial, the angle would increase back to 90°). After either 4 reversals, or reaching a 10° angle (whichever happened first), the second part of the experiment began, in which a 'two-down, one up' rule was implemented for the remainder of the session. In this part, the staircase step size was 10% of the current angle. The step-size for walking angles below 5° (from straight ahead) was set to 1°. The experiment ended when 8 reversals were obtained. The (absolute) angle values in the last 6 reversals were averaged to assess the discrimination threshold. Alternatively, the subject's threshold was set to 90° or 1°, if 6 consecutive mistakes were made in 90° trials, or 6 consecutive correct responses were made in 1° trials, respectively. An example of raw staircase data is shown in Figure 3B.

In this experiment, in addition to a variance in trial duration (again, there was no instruction to answer quickly), the *number* of trials also varied between participants (in accordance with the adaptive staircase procedure). In practice, all subjects finished the experiment after 33-73 trials (late-sighted group mean: 44 trials; control group mean: 53 trials). The overall experiment duration (including the inclusion task, see inclusion criteria and tests below) was 8-10 minutes.

Body-Posture Emotion Discrimination task

Twenty-one late-sighted and 41 Control participants (29 Israeli, 12 Ethiopian) completed the *Body-Posture Emotion Discrimination* experiment (Figure 4).

The stimuli consisted of 20 static images of 20 individuals standing in prototypical postures conveying either anger (10 stimuli) or fear (10 stimuli) taken from the BESST body postures pictures set.[42] The face in each image was obscured by a grey ellipse. Stimuli sizes differed slightly between trials, depending on the body-posture. Each figure was about 19 X 12 cm on the screen, corresponding to 26.7 X 17.1 visual degrees, at a 40 cm distance from the screen.

In each trial, a static image of an actor's body was presented (see Figure 4A). On the same screen, two colored circles were shown (red: bottom-left, blue: bottom-right) and subjects indicated whether the actor appeared angry or frightened, by pressing the corresponding colored-circle on the touch screen (Red-angry, Blue-frightened). Following report, a blank ITI screen appeared for 300 ms, after which the next trial began. The experimental task consisted of a single block in which each stimulus was presented once (for a total of 20 trials), with presentation order randomized for each participant. Although each stimulus was presented once, no feedback was provided, since other tasks (not reported here) using similar stimuli could have been affected by it. Participants were encouraged to emphasize accuracy rather than speed, and the time until response was not limited. Thus, experiment duration varied between participants, but in most cases they finished (including instructions and examples) within 10 minutes.

QUANTIFICATION AND STATISTICAL ANALYSIS

Behavioral data were processed and analyzed using MATLAB R2019b (version 9.7.0, Mathworks, Natick, MA). Subsequent statistical analyses were performed using SPSS (version 26.0, SPSS, Chicago, IL).

Performance metrics

In the *Social-Interactions*, *Joint-Orientation* and *Body-Posture* experiments, accuracy (percent of correct responses) was used to measure performance. In the *BM Walking-Direction* experiment, performance was assessed based on the threshold of distinguishable walking direction (in degrees).

Participants were instructed to favor accuracy over speed and were given unlimited time to respond. Thus, reaction times (RTs) were not used to assess performance. However, we assured that no speed-accuracy tradeoff occurred: late-sighted participants were generally slower than controls (in addition to less accurate). RTs were analyzed only for correct trials, excluding those below 200 milliseconds (ms) or exceeding the mean RT ± 3 SD. In the *Social-Interactions* experiment, the late-sighted participants' mean RTs were 1668 ms for *Full-Body Animations*, 1829 ms for *Static-Snapshots*, and 1957 ms for *PLD*, compared to 911, 1001 & 1059 ms for Israeli controls, and 982, 1037 & 1024 ms for Ethiopian controls. In the *Joint-Orientation* tasks, late-sighted participants averaged 1465 ms (*Full-Body Animation*) and 1572 ms (*Static-Snapshots*), while Israeli controls averaged 1000 & 780 ms, respectively. In the *Body-Posture* task, trial durations averaged 3893 ms for late-sighted participants, 1688 ms for Israeli controls, and 1622 ms for Ethiopian controls. Finally, in the *BM Walking-Direction* task, late-sighted participants had an average trial duration of 3624 ms, compared to 2905 ms for Israeli controls.

Inclusion Criteria and Tests

We included in this study only late-sighted children who met the following criteria, prior the operation (pre-op): (1) had clear *nystagmus*, a classical sign of early-onset blindness,[43] (2) in a pre-op ophthalmological examination, had (at least) basic light-perception, and (3) were legally blind before the operation (by the standard definition of legal blindness in the U.S., i.e. visual acuity worse than 6/60, equivalent to 3 cpd). By the WHO standards, these children have *severe vision impairment*.[46]

To ensure that differences between the late-sighted and the control groups do not stem from the blur experienced by the late-sighted participants *after* surgery, we excluded from the study two participants whose *post*-op visual acuity was worse than 3/60 (1.5 cpd; pilot testing suggested that further blur, below 1.5 cpd, could degrade performance in controls). 28 late-sighted participants met this criterion (post-op visual acuity > 1.5 cpd). Accordingly, a blur level corresponding to a cutoff at 1.5 cpd was imposed on all images and videos shown to control subjects in all tests (through low-pass filtering; see image blur control).

In addition, we verified the participants' comprehension and basic ability to perform the tasks, as described below:

Social-interactions, joint-orientation & body-posture experiments

Before beginning the actual task, participants viewed some example trials (in the *Social-Interactions* experiment: at least six examples, 2 from each format (*Full-Body Animation*, *Static-Snapshot*, *PLD*); in the *Joint-Orientation* experiment: at least 4, 2 from each format (*Full-Body Animation*, *Static-Snapshot*); in the *Body-Posture* experiment: at least 4). A prerequisite for beginning the experiment was that the participant was able to see two people in the scene in each of the examples (or a single person, in the *Body-Posture* task), and that to the best of the experimenter's judgment, the task was clear to the participant. When necessary, examples and instructions were repeated until this condition was met. All participants met this condition, after a maximum of two repetitions of the examples. The stimuli (images / videos) presented in the example trials were not shown in the experimental block.

BM walking-direction experiment

Previous work had established that late-sighted children who were treated early (within the first year from birth), can discriminate between biological and scrambled motion, just as well as control subjects.[17] We validated that the *late*-treated participants can also easily perform this discrimination, and used it as an inclusion task. The inclusion task consisted of five trials. In each, subjects were presented with two videos (at the left and right sides of the screen) – one depicting BM of a walking person (in a different direction for each trial) and the other was its scrambled version, created by randomizing the initial position of each dot, while maintaining the original motion trajectories. Subjects were instructed to point to the display depicting *biological* motion (which was randomized between screen sides across trials). All 23 subjects who participated in the *BM walking-Direction* task succeeded in 5/5 trials of the *BM vs. Scrambled* task, thereby passing the inclusion criterion.

Outlier removal

Participants whose results were more than 3 standard deviations above or below the group mean for each task, were considered outliers and were discarded from that specific task. This resulted in the removal of one late-sighted participant and one Israeli control in the *Full-Body Animation* condition of the *Social-Interactions* task; one Israeli control in the *PLD* condition; one Israeli control in the *Static-Snapshot* condition of the *Joint-Orientation* task; and one late-sighted participant and one Ethiopian control in the *Body-Posture* task.

Handling variance and non-normal residuals

Due to the small sample-sizes, it was important to test for inhomogeneity of variances between groups in each experiment, as well as the normality of residuals within each group. To that end, when Levene's test indicated the variances were significantly different between groups and / or the Shapiro-Wilk test indicated non-normality in at least one group, we performed nonparametric tests in addition to the parametric ones reported in the main text. In the case of ANOVAs (for the experiments with 3 groups), we used Kruskal–Wallis, followed by Dunn's post-hoc comparisons, with Cliff's delta (Δ) as the nonparametric effect size measure (indicating the degree of dominance of one group over another[48]). For independent t-tests (in experiments with 2 groups), we used the Mann-Whitney U Test. Details of the statistical tests and results are given below.

Social-interactions experiment

Levene's test indicated unequal variances between groups in the *Full-Body Animation* task ($F(2, 65) = 5.16$, $p = .008$). In addition, the Shapiro-Wilk test indicated a non-normal distribution in both control groups (Ethiopian: $W(16) = .88$, $p = .044$; Israeli: $W(29) = .82$, $p < .001$). We thus performed the Kruskal–Wallis test, which indicated a significant group effect ($H(2) = 39.64$, $p < .001$). In the *Static-Snapshot* and *PLD* tasks, we got a null result in Levene's test (*Static-Snapshot*: $F(2, 67) = .247$, $p = .782$; *PLD*: $F(2, 66) = .663$, $p = .519$), supposedly indicating homogeneous variances. However, the Shapiro-Wilk test indicated a non-normal distribution in the Israeli control group, in both tasks (*Static-Snapshot*: $W(30) = .91$, $p = .017$; *PLD*: $W(29) = .93$, $p = .048$). We therefore performed the Kruskal–Wallis test, and indeed the group effects remained significant (*Static-Snapshot*: $F(2, 38) = 24.11$, $p < .001$; *PLD*: $F(2, 36) = 26.96$, $p < .001$). Results of Dunn's post-hoc comparisons are given in the main text.

Joint-orientation experiment

Levene's test indicated unequal variances in both tasks (*Full-Body Animation*: $F(43) = 16.06$, $p < .001$; *Static-Snapshot*: $F(42) = 8.91$, $p = .005$). Degrees of freedom were adjusted accordingly from 43 to 22 and from 42 to 24, in the *Full-Body Animation* and *Static-Snapshot* tasks respectively. Results of the t-tests with the adjusted degrees of freedom are reported in the main text. In addition, the Shapiro-Wilk test indicated a non-normal distribution in both groups in the *Full-Body Animation* task (Controls: $W(27) = .69$, $p < .001$; late-sighted: $W(18) = .86$, $p = .012$), and in the control group in the *Static-Snapshot* task ($W(26) = .64$, $p < .001$). We thus performed the Mann-Whitney U test, which confirmed the control group had significantly higher performance than the late-sighted in both tasks (*Full-Body Animation*: $U = 124.5$, $p = .003$; *Static-Snapshot*: $U = 114.5$, $p = .002$).

BM walking-direction experiment

Levene's test indicated unequal variances ($F(51) = 13.72$, $p = .001$). Degrees of freedom were adjusted accordingly from 51 to 29. Results of the t-test with the adjusted degrees of freedom are reported in the main text. The Shapiro-Wilk test indicated that the data of both groups is normally distributed (both p's $> .1$).

Body-posture experiment

Levene's test indicated unequal variances ($F(2, 59) = 8.98$, $p < .001$), and the Shapiro-Wilk test indicated a non-normal distribution in both control groups (Ethiopian: $W(12) = .78$, $p = .005$; Israeli: $W(29) = .86$, $p = .002$). We thus performed the Kruskal–Wallis test, which indicated a significant group effect ($H(2) = 21.45$, $p < .001$). Results of Dunn's post-hoc comparisons are given in the main text.