Form Perception as a Bridge to Real-World Functional Proficiency

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Abstract

Recognizing the limitations of standard vision assessments in capturing the real-world capabilities of individuals with low vision, we investigated the potential of the Seguin Form Board Test (SFBT), a widely-used intelligence assessment employing a visuo-haptic shape-fitting task, as an estimator of vision's practical utility. We present findings from 23 children from India, who underwent treatment for congenital bilateral dense cataracts, and 21 control participants. To assess the development of functional visual ability, we conducted the SFBT and the standard measure of visual acuity, before and longitudinally after treatment. We observed a dissociation in the development of shape-fitting and visual acuity. Improvements of patients' shape-fitting preceded enhancements in their visual acuity after surgery and emerged even with acuity worse than that of control participants. Our findings highlight the importance of incorporating multi-modal and cognitive aspects into evaluations of visual proficiency in low-vision conditions, to better reflect vision's impact on daily activities.

Keywords: form perception, functional vision, visual restoration, multisensory integration.

Introduction

Assessing residual visual capabilities of individuals with vision loss poses a multifaceted challenge. Standard measures such as visual acuity, contrast sensitivity, and visual field tests, which quantify visual 'capacity' or ability in controlled environments, are commonly employed in clinical settings as a proxy for an individual's visual 'performance' in the context of a social environment. However, these standard visual measures often fall short in precisely capturing functional vision – the actual utility of vision for visually-related activities in practical, everyday scenarios (Bennett et al., 2019; Castañeda et al., 2016; Colenbrander, 2003; Morelli et al., 2020).

The disparity between standard measures of basic low-level ability and functional vision is evident in the gaps (Humayun et al., 2012; Manley et al., 2022) observed between these conventional visual metrics and more naturalistic and multisensory assessments (Cappagli et al., 2017; Gori et al., 2012). This disparity underscores the need for evaluations which encompasses the complexities of active multi-modal interactions typical of daily life.

In this study, we evaluated visuo-haptic form perception for assessing functional vision. The choice of form perception was driven by its intricate nature and functional importance. The ability to visually recognize and categorize forms is crucial for daily-life tasks such as identifying objects, understanding spatial layouts, and comprehending visual scenes. Moreover, the recognition of visual shapes plays a fundamental role in key areas of learning, including reading

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and mathematics (Hawes et al., 2015). The kinesthetic and tactile inputs and its integration with visual information additionally contributes to the ecological value of the task.

We adopted the Seguin Form Board Test (SFBT, Venkatesan, 2014) as a functional vision task. Comprising 10 geometric wooden blocks to be fitted into corresponding slots on a wooden board, the SFBT has a rich history. Originally designed in 1856 as an intelligence test, it has endured as a widely utilized measure of mental age (Venkatesan, 2009, 2014), which correlates with other intelligence tests and with indicators of social maturity (Koshy et al., 2017).

To explore the usefulness of a visuo-haptic shape-fitting as a measure of functional vision, we evaluated the performance of children and adolescents on this task as well as on the standard measure of visual acuity, both tested before and following cataract-removal surgery aimed at restoring sight. Shape-fitting is apt for assessing early recovery from congenital blindness as these patients can match and identify visual shapes (McKyton et al., 2015) and rapidly begin to integrate haptic and visual shape information following treatment (Chen et al., 2016; Held et al., 2011; Senna et al., 2021).

By examining performance longitudinally, we sought to discern the influence of visual experience on task proficiency and the development of functional vision. This endeavor represents the initial step toward validating the potential applicability of the SFBT as a measure of functional vision.

Methods

Participants

Twenty-three newly sighted children participated in the study. These individuals were born with bilateral dense cataracts which obstructed their line of sight. They remained visually inexperienced until late childhood, while attaining neural and motor maturity. The children were identified by the Project Prakash outreach team and received surgical sight-restoring cataract-removal at the Schroff Charity Eye Hospital in New-Delhi, India. This allowed us the unique opportunity to spotlight the development of functional vision. Additionally, twenty-one typically sighted age-matched children were tested on this task as control participants. These children were recruited from Delhi schools in a neighborhood with similar socioeconomic status as the patient population, and their grade levels were matched to those of patients.

Testing time-points

Patients were tested at six time points: before treatment (*Pre-Operation*), twice after treatment (*Post the 1st- and the 2nd-Eye Operation*) and then thrice again (*Follow-up 1-2 months, 4-6 months,* and *9-12 months after operation*). Due to limitations connected to the COVID pandemic, not all participants could arrive for all testing time points. We were able to collect shape-fitting data from 22 patients prior to operation and post the 1st eye operation, from 12 patients post the 2nd eye operation, and from 19, 16, 14 in the follow-up time-points. Only 5 patients participated in **all** research testing time-points. To explore the effects of repeated testing, 15 of the controls were tested twice (*1st and 2nd* time-points), with a gap of 3-5 days in between testing days, consistent with the time gap between Pre-operative and Post 1st Eye Surgery time-points of testing patients. The remaining controls were tested once.

Figure 1. Materials. *Left*: **The Seguin Form Board Test (SFBT).** *Top*: before. *Bottom*: after. *Right*: **Blurring method.** *Top*: no blur. *Bottom:* intermediate blur level.

Materials

The SFBT (Figure 1, left) consists of 10 black geometric wooden blocks that need to be fitted into the corresponding slots of a form board. To maximize visual contrast, the outline of the wooden slots was highlighted with a thick black marker and placed on a white background.

To simulate the type of acuity reduction conditions that patients experience while performing this task, control participants wore goggles covered with translucent light diffusers that attenuate the higher spatial frequencies and degrade the visual input (so called ‘blur goggles’, Figure 1, right, a method used in e.g. (Gandhi et al., 2017; Gupta et al., 2022, 2023; Senna et al., 2021, 2022)

Experimental design

Seguin Form Board Test Administration. At each testing timepoint the board was fully fitted for three consecutive runs. The task was performed from a standing position, to allow the participants to move freely and reach all the blocks and slots with equal ease. The table was adjusted to the height of the participant, between the knees and hips. Thus, a top-view was maintained, allowing the participant to fully appreciate the visual feedback. The standing position also ensured that all parts of the board and piles were comfortably reachable. The blocks were stacked in three piles on the right side of the child adjacent to the board. The order from bottom to top (Arya, 1980): nearest to the participant star-circle-diamond; oval- triangle-rectangle; and furthest from the participant plus-hexagon-semi circle-square.

The experiment was run in Hindi. The participant were instructed that they will need to fit each block in the slot with a correspondingly shaped block. They were asked to be as quick as possible and were told that they would be timed. When ready, the board and blocks were exposed and the prompt: 'Start! Do it as quickly as you can!' was given by the examiner. This was repeated thrice, with the board rearranged while the participant looked away.

Shape-fitting was performed one block at a time. Each trial consisted of the entire time elapsed between lifting a block and releasing it. Correct fitting was accompanied by natural auditory feedback (the sound of the block clicking into the slot). The experimenter gave feedback regarding performance only at the end of a trial (when the subject released one block and was ready to move on to the next). Positive feedback was given by clapping. Negative feedback was given for (1) incorrect match: "No. This is not the correct placement; find a different shape which this block matches better with" or (2) correct match with incorrect orientation: "This shape isn't completed yet; you need to fix it."

Visual acuity. We ran the computerized Freiburg Visual Acuity Test (FrACT; (Bach, 1996, 2007) from a 40 CM distance with both eyes and repeated with each eye.

Outcome Measures

Shape-Fitting Speed. All sessions were videotaped, and time to complete each run was measured from the video footage using a video editing program (Adobe Premiere), by tallying the frames from the 'Start' prompt to fitting completion. In each testing time-point, the average shape-fitting completion time across three consecutive runs (Venkatesan, 2014) was taken as the metric of real-life proficiency. This metric encompasses both initial encounters with shapes, as well task learning and memory-based enhancements over subsequent attempts, which collectively influence functional proficiency in daily life.

Visual Acuity. The minimum visual angle of the gap that can be resolved by the observer is taken as a measure of the visual acuity. This is expressed by the Logarithm of the Minimum Angle of Resolution (LogMAR; Il & Je, 1976), which notates visual loss; the higher the LogMAR value, the poorer the visual resolution ability. Standard vision, defined as the ability to resolve details as small as 1 minute of visual angle, is scored as LogMAR 0.

Statistical Testing

To compare the ages of patients and controls, and to compare the acuity of patients at each time point with the acuity of controls, we performed independent sample student's t-tests.

To elucidate the early effect of first exposure to unobstructed sight on shape-fitting performance, we performed a mixed-design ANOVA, with Shape-fitting speed as the dependent variable, and the two groups (Patients, Controls) as a between-participant factor (*Group*). To account for the effect of repeated testing, both groups were tested twice within a similar time span of 3-7 days, and the effect of testing time-point (pre-operation versus after 1st eye operation for patients, 1st versus 2nd for controls) as a within-participants factor (*Time-point*).

To test longitudinal development over time from surgery, we performed two separate analyses of repeated measures ANOVA, with visual acuity (LogMAR) as the dependent variable in one and shape fitting speed in the other analysis, and with time from surgery (*Pre-Operation, Post 1st Eye Operation, Post 2nd Eye Operation, 1-2 Months, 4-6 Months, 9-12 Months Follow-ups*) as the within-participants factor (Time-point). Post hoc testing was corrected for multiple comparisons with the Bonferroni correction. To complement these analyses with patients who did not have data for all testing time-points, five separate paired sample student's t-tests were performed between all pairs of consecutive time-points.

To compare the performance of patients and control participants, six separate independent sample student's t-tests were performed between the patient's speed of shape-fitting at each time-point and the control's speed (1st testing point).

To test co-variance between shape-fitting speed and visual acuity, we performed a Pearson correlation between these measures at each of the testing time-points.

Results

Age and acuity of Patients versus Controls

We found no significant age difference between patients and controls, confirming age-matching (M±SD of years: patients 12.26 years ± 4.34; controls 10.42 years ± 1.91, t(41)=-1.8, p=.07). The acuity of controls (measured when wearing blur goggles) matched the post-operative acuity of the patients, after completing both operations (M±SD LogMAR of *controls* 1.36±.41; *patients prior to operation* 1.76±.32, (t(42)=-3.52, p=.001; *after 1st eye operation* 1.70±.29, t(41)=-3.1, p=.003; *after 2nd eye operation* 1.51±.31, t(40)=-1.2, p=.20; *1-2 Months follow-up* 1.44±.41, t(38)=-.5, p=.55; *4-6 Months follow-up* 1.3±.22, t(35)=.53, p=.59; *9-12 Months follow-up* 1.2±.25; t(33)=1.27, p=.21).

Development of visual acuity over Time

The analysis of longitudinal progression of binocular visual acuity in patients with a full dataset (Figure 2A) revealed an effect of Time-point (F(5,20)=14.3, p<.001, η^2_p=.78) which was driven by improvements between non-consecutive time-points (Figure 2A, LogMAR M±SD: *Pre-Operation* 1.76±.30*; Post 1st Eye Operation* 1.51±.21; *Post 2nd Eye Operation* 1.47±.21; *1-2 Months* 1.30±.13; *4-6 Months* 1.32±.23; *9-12 Months* 1.13±.22).

A paired t-test of monocular acuity of the *operated eye* before versus after surgery revealed only marginally significant difference (t(22)=2.03, p=.054, d=.19).

Paired t-tests between consecutive time-points when using both eyes (Figure 3B, top) did not reveal a significant improvement in visual acuity after the *1st Eye Operation* (t(22)=1.3, p=.19, d=.27). An improvement was found after the *2nd eye operations* (t(10)=3.0, p=.01, d=.06), whereas afterwards patients' acuity did not show short-term improvement (no significant improvement between consecutive time-points found: *Post 2^{nd} Eye Operation to 1-2 Months Follow-up*: t(10)=1.2, p=.25, d=.36; *1-2 Months to 4-6 Months Follow-up*: t(14)=.55, p=.58, d=.05 ; *4-6 Months to 9-12 Months Follow-up:* t(12)=1.8, p=.09, d=.24). Thus, the most prominent improvement in patients' visual acuity emerged after the 2^{nd} eye operation.

Early Effect of Sight-restoring Surgery on Shape-fitting Performance

See Figure 3A for individual performance across runs. To test the effects of cataract removal on shape-fitting performance, we compared patients and controls across two time-points. The 1^{st} testing time-point of patients was collected prior to any treatment (*Pre-operation*), and the second within 3-7 days after it (*Post 1^{st} Eye Operation*), whereas controls were tested twice within the same span of time (*1^{st} and 2^{nd} testing*). Shape-fitting speed significantly differed between patients and controls (main effect of Group F(1,34)=9.6, p=.004, η^2_p=.22). Fitting speed significantly decreased in the 2^{nd} versus the 1^{st} testing Time-Point (main effect of Time-point, F(1,34)=13.8, p<.001, η^2_p=.29) and was differently modulated across time-points between the groups (*Group* and *Time-Point* interaction F(1,34)=9.3, p=.004, η^2_p=.22). Post hoc testing revealed that the decrease in speed between time-points was driven solely by the patient group, in which shape-fitting speed was significantly reduced from *pre-operation* (M=148s, SD=137) to *post 1^{st} eye operation* (M=84s, SD=89; t(20)=5.2, p<.001, d=0.73). Conversely, the control group did not show a difference between the *1^{st}* (M=31s, SD=9) and *2^{nd}* (M=24s, SD=8) *testing time-points* (t=.43, p=1, d=.07). This suggests that the improved performance of patients after operation was not likely solely driven by retesting effects, as controls did not exhibit such effects.

Shape-fitting Development over Time from Surgery

To test whether the patients continued to improve thereafter, we ran a repeated measures ANOVA on the five patients with a full dataset of all testing time-points (Figure 2B), which revealed an effect of Time-point (F(5,20)=19.9, p<.001, η^2_p=.83 ; M±SD of time, in seconds: *Pre-Operation* 109±45, *Post 1^{st} Eye Operation* 38±7, *Post 2^{nd} Eye Operation* 29±7, *1-2 Months* 31±6, 4-6 *Months* 25±4, 9-*12 Months* 27±12).

Paired t-tests comparing all patients between consecutive time-points (Figure 3B, Bottom) revealed a significant reduction in shape-fitting speed between the 1^{st} and 2^{nd} eye operations (t(10)=3.0, p=.01, d=.06), whereas after the 2^{nd} eye operation patients' shape-fitting speed plateaued and we did not find significant improvement between consecutive time-points (*Post 2^{nd} Eye Operation to 1-2 Months Follow-up*: t(10)=1.2, p=.25, d=.36; *1-2 Months to 4-6 Months Follow-up*: t(14)=.55, p=.58, d=.05 ; *4-6 Months Follow-up to 9-12 Months Follow-up*: t(12)=1.8, p=.09, d=.24)

While shape-fitting of controls and patients differed in the *Pre-operation* (t(41)=-3.8, p<.001, d=-1.16) and *Post 1^{st} Eye Operation* time points (t(41)=-2.7, p=.009, d=-.83), they did not differ in any of the following time-points (*Post 2^{nd} Eye Operation*: t(31)=-1.6, p=.12, d=-.57 ; *1-2 Months*: t(38)=-1.9, p=.06, d=-.60*; 4-6 Months*: t(35)=-1.5, p=.13, d=-.05 ; 9-12 Months: t(32)=.6, p=.56, d=.20).

Thus, shape-fitting speed decreased after the 1^{st} eye operation, while the acuity of patients was still poorer than that of controls. The improvement of shape-fitting performance was evident prior to their visual acuity enhancement. Shape-fitting continued to improve after the 2^{nd} eye operation, reaching the speed of controls, and then plateaued and did not change in consecutive testing points.

Relationship of Visual Acuity and Shape-fitting

Visual acuity of controls correlated with shape-fitting speed across individuals (r=0.57, p=.008). Similarly, visual acuity of patients correlated with shape-fitting speed in several of the tested time-points (*Pre-operation* r=.48, p=.02; *Post 1^{st} Eye Operation* r=.64, p=.001 ; *1-2 Months* r=.67, p=.004; *9-12 Months* r=.70, p=.007) but not *Post 2^{nd} Eye Operation* (r=.40, p=.19) and in the *4-6 Months* (r=.18, p=.49).

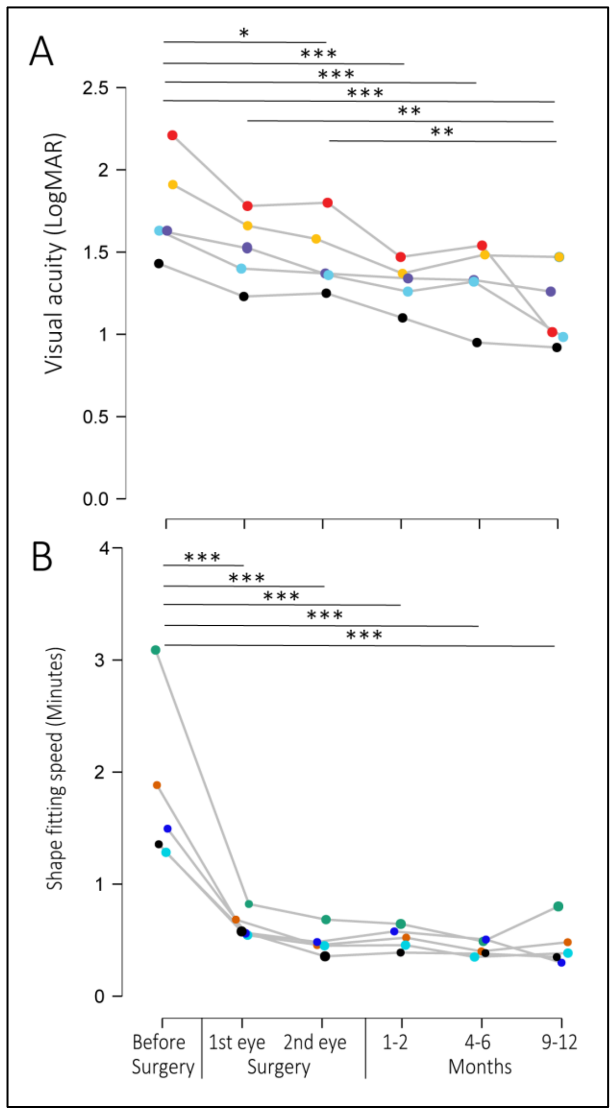

Figure 2. The development of binocular visual acuity (**A**) and shape-fitting speed (**B**) in patients (n=5) across time.

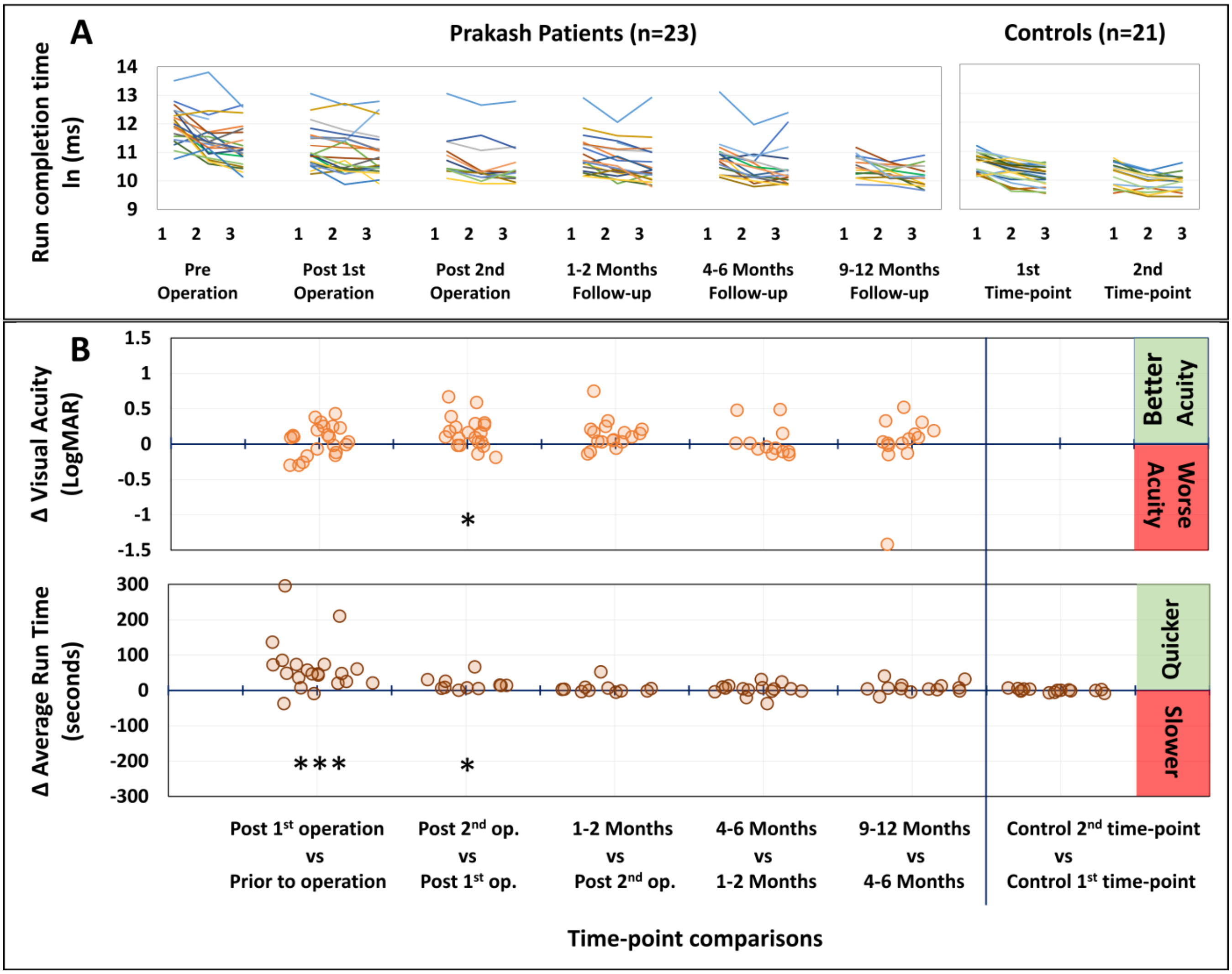

Figure 3. A. Speed of the three runs of all patients (left) and controls (right) across time, natural logarithm (ln) scale (ms). **B.** Difference in visual acuity (*Top*) and in shape-fitting speed (*Bottom*) of individual patients (left) and controls (right) between consecutive testing time-points. Acuity improved after the 2nd eye operation, whereas shape-fitting became quicker already after the 1st eye operation, continued to improve after the 2nd eye operation, and then plateaued.

Discussion

In this paper, we challenge the prevailing clinical approach that relies solely on low-level visual metrics (such as visual acuity, contrast sensitivity, and visual fields) to assess the capabilities of patients with low vision. We propose the integration of assessments that provide estimates of vision's practical utility in real-world contexts. Towards this objective, we explored the effectiveness of the SFBT, a visuo-haptic shape-fitting test, for evaluating functional vision. We examined the evolution of shape-fitting speed over time following cataract-removal surgery and compared it with the progression of visual acuity, aiming to discern associations and dissociations between the two metrics.

Improvement in shape-fitting, quantified as decrease in the average speed (between three consecutive runs) of completing the SFBT, arose in sight-restored patients as soon as the obstructing cataract was removed from one of the eyes. This improvement was not likely accounted for by retesting effects, since control subjects did not demonstrate significant improvement between two consecutive testing sessions conducted several days apart. Shape-fitting speed continued to improve after the operation of the 2nd eye and stabilized thereafter.

Shape-fitting speed and visual acuity co-varied across individuals, exhibiting a correlation in both patients and controls. However, visual acuity does not appear to be the primary factor driving the improvement in shape-fitting among patients, as indicated by comparing the timeline of enhancements. Notably, the improvement in shape-fitting performance preceded the enhancement in visual acuity. This improvement emerged soon after the 1st eye operation, a period during which patients had considerably poorer acuity compared to controls. Visual acuity in the early period after surgery is typically unstable due to various factors (e.g., sutures which distort the shape of the eyeball, pupil dilating medication around the clock). Once the sutures are removed and corrective eyeglasses are prescribed, the effects of the surgery on visual acuity become fully apparent. The improvement of shape-fitting speed under such conditions suggests that shape-fitting is not an acuity limited task.

The observed dissociation between low-level visual acuity and shape-fitting functional skills may be attributed to the different nature and level of control of the two tests. The SFBT is a naturalistic task, in which participants are active and are free to optimize their environmental conditions by close-viewing and movements of their head and of the visual target (Figure 4, bottom). In contrast, visual acuity assessments are strives to quantify the ability to resolve high frequency visual detail in in a static environment at fixed viewing distances. Moreover, the SFBT encompasses the complexities of active multisensory integration typical of daily life (Murray et al., 2016), whereas visual acuity testing examines a specific aspect of visual function, in isolation from other modalities.

Finally, it has been shown that visual form perception relies on a complex process that combines bottom-up visual processing of contour information with top-down processing that draws on prior experiences and stored knowledge (Lederman & Klatzky, 1990; Augustine et al., 2011; Renzi et al., 2013). Thus, spatial memory, heuristic utilization, and overall resourcefulness can all significantly contribute to performance on the SFBT. This is a reflection of conditions in real-life scenarios, in which the use of low-level visual information is not isolated, and multiple abilities and sources of information are relied upon for completing tasks.

Future Directions

We will perform additional analysis to document the specific confusions made between shapes during the test. This will allow us to examine which shape attributes (size, edges, geometrical concept etc.) were most confused with one another. This should reflect the most salient cues relied on by the newly sighted for shape-fitting (Chen et al., 2016; Orlov et al., 2021; Ostrovsky et al., 2010) and allude to the cues that are important during the development of form perception.

To confirm the validity of the SFBT as a measure of visual ability in individuals with low vision, we will examine if it co-varies with performance on other complex perceptual tasks, including but not limited to face perception (Gilad-Gutnick et al., 2019), motion coherence detection thresholds (Raja et al., 2023) and human movement perception (Ben-Ami et al., 2022, 2023). To gauge the effects of familiarity and of top-down use of prior knowledge, we will examine the relationship between the ability to name specific shapes and the speed and errors of fitting them (Knights & Olver, 1967; Koestline et al., 1972).

Given the association between shape-fitting and mental age in sighted individuals, future work could examine if this extends to individuals with vision loss, by within individuals scores on cognitive tests adapted for low vision (Aprile et al., 2020; Cassar et al., 2022; Reid, 2002), as well as measures of daily function and independence (Koshy et al., 2017; Roopesh, 2020) with shape-fitting speed.

Finally, we are exploring an adaptation of the form board which focuses on feedback from the visual modality. The task involves fitting flat shapes enclosed inside translucent round cards onto a two-dimensional form board with outlines of these shapes. The center of each shape is lined with magnets, allowing the participant to rotate and adjust the orientation of the card on top of shape outlines on the poster based on visual cues (See Figure 4). This adaptation can not only be used to explore recovery of functional vision, but can potentially serve for training on the use of visual feedback.

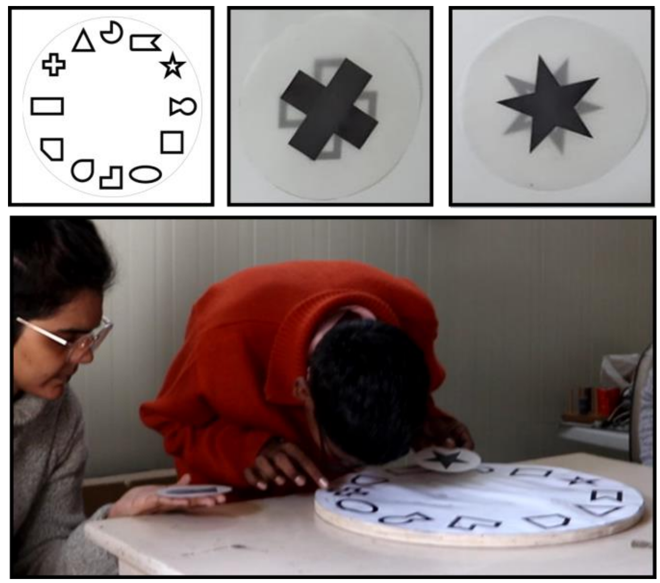

Figure 4. Visual form poster test. *Top. left*: Form poster. *Middle and right*: cards – correctly placed, incorrectly oriented. Bottom: visual shape-fitting experiment. The patient is counting the edges of a plus shape to differentiate from the star card he is trying to match.

In summary, while visual acuity has become a short-hand metric for describing a person's vision, our results indicate a dissociation between functional skills and visual acuity. Hence, we argue that characterization of functional visual skills needs to include metrics that go beyond visual acuity. It is imperative that guidelines and policies for sight evaluations extend beyond sensitivity to low-level features of the visual scene and incorporate tasks that reflect the practical usefulness of vision in real-world contexts.

Pending further validation, we posit that shape-fitting tests have the potential to supplement traditional vision assessments, offering a broader insight into functional abilities.

Quantifying the practical utility of newly acquired or improved vision for daily activities will allow a more comprehensive assessment of visual outcomes. This approach can enhance the evaluation of outcomes from vision-restoring interventions, rehabilitation programs, vision prostheses, and visual sensory substitution devices.

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