Supplemental Material

1. CVI Diagnosis

Diagnosis involved a comprehensive ophthalmic evaluation, including visual acuity, contrast sensitivity, visual field perimetry, and ocular motor functions, as well as a thorough refractive and ocular examination. Assessment of functional vision abilities and challenges was obtained using structured questionnaires, observational tasks, and activity-based surveys (McCulloch et al., 2007; Ortibus et al., 2020). Review of medical history and any available neuroimaging or electrophysiological data was also integrated as part of the formal diagnosis (see Boonstra et al., 2022; Fazzi et al., 2007; McConnell et al., 2021; Pilling et al., 2023).

References

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McCulloch DL, Mackie RT, Dutton GN, Bradnam MS, Day RE, McDaid GJ, Phillips S, Napier A, Herbert AM, Saunders KJ, Shepherd AJ. A visual skills inventory for children with neurological impairments. Dev Med Child Neurol. 2007 Oct;49(10):757-63.

McConnell EL, Saunders KJ, Little JA. What assessments are currently used to investigate and diagnose cerebral visual impairment (CVI) in children? A systematic review. Ophthalmic Physiol Opt. 2021 Mar;41(2):224-244.

Ben Itzhak N, Vancleef K, Franki I, Laenen A, Wagemans J, Ortibus E. Visuoperceptual profiles of children using the Flemish cerebral visual impairment questionnaire. Dev Med Child Neurol. 2020 Aug;62(8):969-976.

Pilling RF, Allen L, Bowman R, Ravenscroft J, Saunders KJ, Williams C. Clinical assessment, investigation, diagnosis and initial management of cerebral visual impairment: a consensus practice guide. Eye (Lond). 2023 Jul;37(10):1958-1965.

2. Modeling results

We report parameter estimates as standardized beta values (Std, β), standard errors (SE), 95% confidence intervals (95% CI), and p-values. Significant results are marked in bold font with significance codes corresponding to the following levels: * p < 0.05; ** p < 0.01; *** p < 0.001.

(See Section 2.5 for full analysis details)

1. Walking Outcomes

Table S1. Preferred walking speed

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**0.21**	**0.032**	**[0.20, 0.22]**	**0.002**	**
Age	**0.02**	**0.001**	**[0.008, 0.03]**	**< 0.001**	***
Group	**-0.43**	**0.001**	**[-0.45, -0.41]**	**< 0.001**	***

2. Primary Collision Detection Metrics

Table S2. Target detection

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	4.03	2.158	[2.98, 5.09]	0.114	
Age	0.09	0.088	[-0.50, 0.69]	0.758	
Group	**-2.92**	**0.776**	**[-4.44, -1.40]**	**< 0.001**	***
Density (medium)	-0.31	0.380	[-1.06, 0.43]	0.412	
Density (high)	-0.47	0.370	[-1.20, 0.25]	0.202	
Group × Density (medium)	-0.22	0.451	[-1.10, 0.67]	0.633	
Group × Density (high)	0.20	0.443	[-0.66, 1.07]	0.644	

Table S3. Response time

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**0.67**	**0.175**	**[0.33, 1.02]**	**< 0.001**	***
Age	0.06	0.112	[-0.16, 0.27]	0.610	
Group	**0.73**	**0.266**	**[0.21, 1.25]**	**0.006**	**
Density (medium)	**0.19**	**0.022**	**[0.15, 0.24]**	**< 0.001**	***
Density (high)	**0.25**	**0.022**	**[0.21, 0.29]**	**< 0.001**	***
Group × Density (medium)	**-0.08**	**0.038**	**[-0.16, -0.003]**	**0.041**	*
Group × Density (high)	**-0.11**	**0.038**	**[-0.18, -0.03]**	**0.005**	**

Table S4. Collision rate

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**-5.46**	**2.081**	**[-6.90, -4.02]**	**0.039**	*
Age	-0.17	0.083	[-0.73, 0.39]	0.545	
Group	**2.54**	**0.901**	**[0.77, 4.31]**	**0.005**	**
Density (medium)	1.11	0.677	[-0.22, 2.43]	0.102	
Density (high)	1.16	0.675	[-0.16, 2.48]	0.086	
Group × Density (medium)	0.09	0.734	[-1.35, 1.53]	0.903	
Group × Density (high)	-0.23	0.733	[-1.67, 1.20]	0.750	

3. Visual Scanning and Gaze Metrics

Table S5. Signed head rotation

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	-0.03	3.451	[-0.18, 0.11]	0.099	
Age	0.06	0.141	[-0.03, 0.14]	0.184	
Group	**0.26**	**1.295**	**[0.04, 0.49]**	**0.026**	*
Density (medium)	0.02	0.764	[-0.12, 0.15]	0.801	
Density (high)	-0.05	0.776	[-0.18, 0.09]	0.509	
Group × Density (medium)	-0.19	1.245	[-0.41, 0.02]	0.083	
Group × Density (high)	-0.01	1.230	[-0.23, 0.20]	0.914	

Table S6. Absolute head rotation

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**1.94**	**0.697**	**[1.65, 2.23]**	**< 0.001**	***
Age	-0.09	0.029	[-0.29, 0.10]	0.355	
Group	0.02	0.235	[-0.44, 0.48]	0.945	
Density (medium)	0.04	0.043	[-0.05, 0.12]	0.409	
Density (high)	0.004	0.044	[-0.08, 0.09]	0.926	
Group × Density (medium)	0.01	0.071	[-0.13, 0.15]	0.919	
Group × Density (high)	0.08	0.070	[-0.06, 0.22]	0.245	

Table S7. Time to first fixation

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	0.002	0.080	[-0.16, 0.16]	0.985	
Age	0.04	0.052	[-0.06, 0.14]	0.426	
Group	**0.47**	**0.124**	**[0.23, 0.72]**	**< 0.001**	***
Density (medium)	0.09	0.068	[-0.04, 0.22]	0.174	
Density (high)	0.03	0.068	[-0.11, 0.16]	0.675	
Group × Density (medium)	0.06	0.102	[-0.13, 0.26]	0.525	
Group × Density (high)	-0.06	0.104	[-0.27, 0.14]	0.532	

Table S8. Fixation duration

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**-0.19**	**0.367**	**[-0.39, 0.008]**	**0.001**	**
Age	0.08	0.015	[-0.05, 0.21]	0.238	
Group	0.13	0.139	[-0.21, 0.47]	0.460	
Density (medium)	**0.23**	**0.064**	**[0.08, 0.39]**	**0.003**	**
Density (high)	0.11	0.064	[-0.05, 0.27]	0.170	
Group × Density (medium)	0.18	0.111	[-0.10, 0.45]	0.208	
Group × Density (high)	-0.04	0.112	[-0.32, 0.23]	0.750	

Table S9. Number of fixations

Parameter	*Std, β*	*SE*	*95% CI*	*p*
Intercept	-0.03	0.060	[-0.15, 0.09]	0.624
Age	0.06	0.032	[-0.001, 0.12]	0.052
Group	0.01	0.108	[-0.20, 0.22]	0.932
Density (medium)	0.05	0.079	[-0.10, 0.21]	0.501
Density (high)	0.04	0.079	[-0.11, 0.20]	0.584
Group × Density (medium)	-0.05	0.140	[-0.33, 0.22]	0.709
Group × Density (high)	-0.09	0.141	[-0.37, 0.19]	0.523

Table S10. Visual scan path

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**4.78**	**0.042**	**[4.70, 4.86]**	**< 0.001**	***
Age	**-0.10**	**0.018**	**[-0.13, -0.06]**	**< 0.001**	***
Group	**0.27**	**0.059**	**[0.15, 0.38]**	**< 0.001**	***
Density (medium)	0.01	0.054	[-0.10, 0.11]	0.904	
Density (high)	-0.03	0.053	[-0.14, 0.07]	0.566	
Group × Density (medium)	0.07	0.081	[-0.09, 0.23]	0.360	
Group × Density (high)	0.01	0.081	[-0.15, 0.17]	0.861	

4. Avoidance Behavior Metrics

Table S11. Signed pathing deviation

Parameter	*Std, β*	*SE*	*95% CI*	*p*
Intercept	0.02	0.058	[-0.14, 0.18]	0.100
Age	-0.08	0.002	[-0.18, 0.02]	0.110
Group	0.001	0.021	[-0.25, 0.25]	0.993
Density (medium)	-0.03	0.011	[-0.16, 0.10]	0.631
Density (high)	-0.07	0.011	[-0.20, 0.07]	0.318
Group × Density (medium)	-0.03	0.018	[-0.24, 0.19]	0.811
Group × Density (high)	0.03	0.018	[-0.19, 0.24]	0.811

Table S12. Mean absolute deviation

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**-2.45**	**0.125**	**[-2.70, -2.21]**	**< 0.001**	***
Age	0.01	0.083	[-0.15, 0.17]	0.881	
Group	0.29	0.197	[-0.10, 0.68]	0.141	
Density (medium)	**-0.29**	**0.042**	**[-0.38, -0.21]**	**< 0.001**	***
Density (high)	**-0.29**	**0.043**	**[-0.37, -0.20]**	**< 0.001**	***
Group × Density (medium)	**0.22**	**0.068**	**[0.09, 0.36]**	**0.001**	**
Group × Density (high)	**0.42**	**0.068**	**[0.29, 0.55]**	**< 0.001**	***

Table S13. Spatio-temporal collision envelope

Parameter	*Std, β*	*SE*	*95% CI*	*p*	
Intercept	**1.33**	**0.389**	**[1.16, 1.51]**	**< 0.001**	***
Age	-0.04	0.016	[-0.17, 0.09]	0.540	
Group	**0.36**	**0.133**	**[0.10, 0.63]**	**0.006**	**
Density (medium)	-0.07	0.038	[-0.14, 0.009]	0.077	
Density (high)	**-0.09**	**0.038**	**[-0.17, -0.01]**	**0.017**	*
Group × Density (medium)	0.04	0.057	[-0.07, 0.16]	0.440	
Group × Density (high)	0.09	0.057	[-0.02, 0.21]	0.098	

3. Case series comparing individual CVI participant results and avoidance strategies

Individual CVI participants showed a broad variability in their behavioral performance, reflecting the adoption of unique compensatory strategies to complete the immersive VR pedestrian collision-avoidance task. In this case-series comparison, we selected three CVI participants to illustrate this observed variability in performance along with a representative control.

Representative control participant (Video S1)

This 24-year-old male participant illustrates a representative profile of the pedestrian collision avoidance behavior observed in our control sample. His preferred walking speed of 0.98 m/s was within the range of the control group means (mean = 1.19 m/s ± 0.16 SD). His overall behavioral performance was also at ceiling, detecting 100% of targets, with 0% collisions, with an average response time of 1.91 seconds and a time to first fixation of 0.36 seconds. The participant also showed little overall pathing deviation (average absolute pathing deviation of 0.09 m).

Figure S1A shows a single frame from the reconstructed data (see video S1) in which the walking trajectories of the participant, the colliding pedestrian (+20° bearing angle and from the high-density crowd condition), and the various noncolliding pedestrians (various colors) are shown. The logged data are depicted from a top-down perspective (left panel) and the corresponding walking speed time series (right panel).

Note that this control participant reached a steady walking speed before the appearance of the pedestrians, and he detected and fixated on the colliding target roughly 2 seconds later. He maintained fixation until the target passed and slowed his walking speed to avoid a potential collision, without deviating from his overall path trajectory. He then resumed his observed walking speed until the end of the trial. This behavioral profile of slowing down to let the target pass (and with minimal pathing deviation) to avoid the collision was the most frequently adopted strategy observed in our control sample.

CVI participant 3 (Video S2)

CVI participant 3 was a 29-year-old female and had a documented lower peripheral visual field deficit. This individual was among the slowest walking participants tested, with a preferred walking speed of 0.57 m/s, which was slower than both the group means for CVI (mean = 0.77 m/s ± 0.22 SD) and controls (mean = 1.19 m/s ± 0.16 SD. She detected only 69.40% of targets, collided with 15.30%, and had a mean response time of 2.84 seconds. On average, she took 1.70 seconds to fixate on the target for the first time, with an average absolute pathing deviation of 0.21 m.

Figure S1B shows that on this trial, the participant walked until she reached her preferred walking speed, then slowed considerably when the other pedestrians appeared. She then correctly fixated on the target and made a series of large leftward side steps (almost 2 m in distance) between her and the target colliding pedestrian. Due to this more pronounced and earlier slowing and sidestepping response, she also failed to pass through the gap between the nearest noncolliding pedestrian. This resulted in the other noncolliding pedestrians now becoming unintended risks for further collisions.

This overly cautious, slower walking profile resulted in two notable outcomes. First, the participant typically failed to reach the intended collision point in time for the target collision event to occur, and second, the slower walking speed caused non-colliding pedestrians to become unintended colliding pedestrians as she entered their walking paths. In cases where she was able to reach the intended collision point, she also showed more exaggerated pathing deviations. Thus, for this individual, adopting this strategy may lead to additional and unintended collision risks. This apparent cascade of emergent collision events also reflected her own self-report descriptions, including feeling highly anxious in very crowded environments.

CVI participant 4 (Video S3)

CVI participant P4 was a 27-year-old female and had a documented left peripheral visual field deficit. Her preferred walking speed of 1.00 m/s was faster compared to the CVI group (mean = 0.77 m/s ± 0.22 SD). This participant was among the higher performers in the CVI group, having detected 100% of the targets with 0 collisions and an average response time of 2.74 seconds. On average, she took 2.24 seconds to fixate the target for the first time on a given trial and made an average absolute pathing deviation of 0.05 m. Interestingly, we noted that this participant showed an apparently counterintuitive strategy of increasing her walking speed as a function of greater crowd density to avoid potential collisions.

Figure S1C illustrates that the participant reached her preferred walking speed before the appearance of the pedestrians, then steadily increased her walking speed after successfully detecting the target and

maintained this behavior for the duration of the trial. Interestingly, the detection response occurred without fixation on the target, suggesting that she was potentially relying more on other potential cues to navigate through the crowd. This participant also made a much smaller pathing deviation during her avoidance of the colliding pedestrian.

This general strategy may be driven by monitoring the coarse patterns of local optic flow related to looming to help identify sufficiently large apertures for passing, then ramping up her walking speed to avoid the collision. Based on her own self-report, the participant confirmed that when faced with larger crowds, she relies less on the detection of other surrounding individuals, but rather prefers to walk at a higher rate of speed so that other surrounding pedestrians can notice and actively avoid her.

CVI Participant 11 (Video S4)

CVI participant P11 was an 18-year-old male and had a documented right homonymous hemianopia. He underwent extensive visual field awareness and visual scanning exercises as part of his rehabilitative training. His preferred walking speed was 0.80 m/s, which was comparable to the CVI group (mean = 0.77 m/s ± 0.22 SD). Despite having a very dense and complete hemifield loss, he was one of the top-performing CVI participants, detecting 91.70% of targets, having only an 8.30% collision rate, and an average response time of 2.26 seconds. On average, he took 1.43 seconds to fixate the target for the first time on a given trial, and he made an average absolute pathing deviation of 0.12 m. Furthermore, he showed no apparent bias in target detection, collision avoidance, and visual scanning behaviors when comparing colliding pedestrian targets occurring on his intact and blind side.

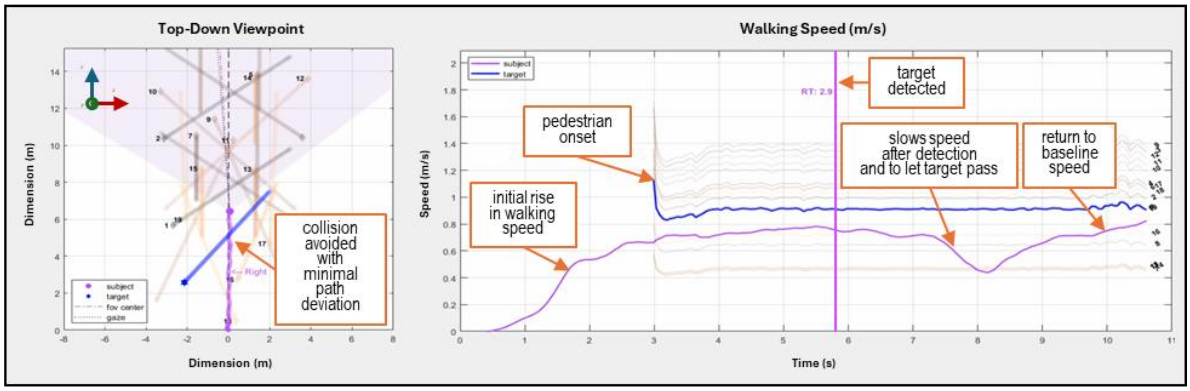
Figure S1D shows that the participant reached his preferred walking speed at the onset of the pedestrians and maintained a steady walking speed throughout the trial. Interestingly, he did not fixate the target, but rather gazed past it, effectively maintaining the target within his intact visual hemifield. He also initiated his collision avoidance behavior early on (at approximately 2 m distance) with a moderate pathing deviation of approximately 0.5 m.

Despite having a dense hemianopic visual field deficit, this individual illustrates an example of employing effective compensatory behaviors (e.g., by active scanning) to avoid pedestrian collisions, even in highly crowded environments.

Taken together, these examples illustrate the value of this immersive HMD assessment to help objectively characterize highly individualized behavioral strategies and the real-world experiences reported by this clinical population.

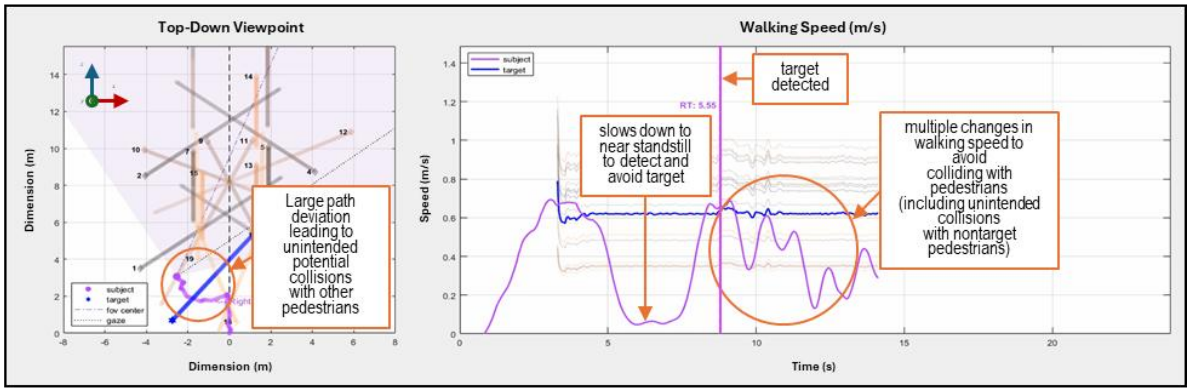
A

Control



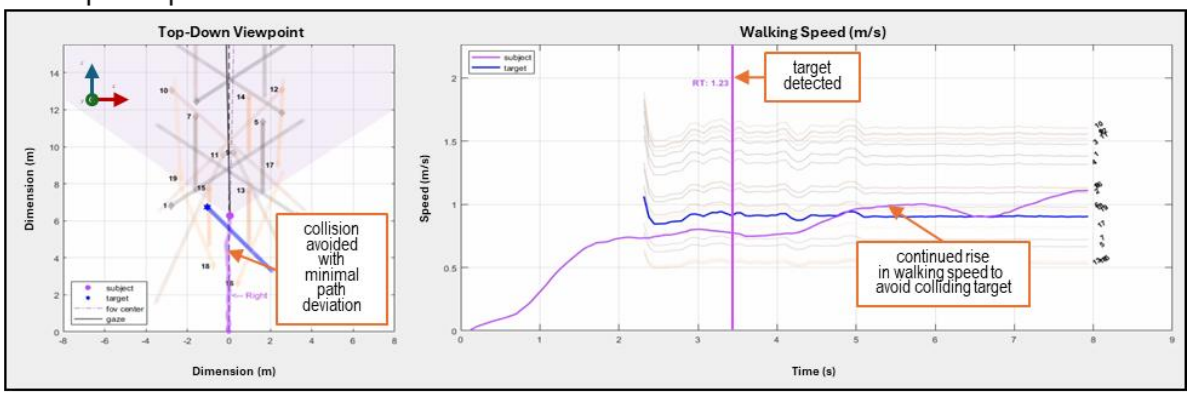
B

CVI participant 3



C

CVI participant 4



D

CVI participant 11

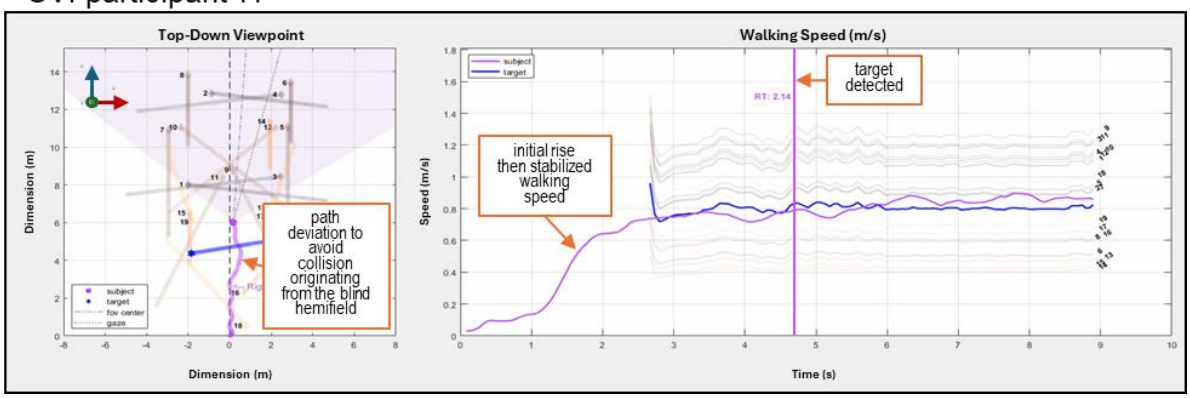


Figure S1. Comparison of individual participant results and avoidance strategies. Still frames taken from representative control (A) and three CVI (B-D) participants (see corresponding Supplementary Videos S1-S4). Left panels depict a top-down view of the path taken by the participant (pink) toward an intended collision with the target pedestrian (blue) (see also figure 1C for further details). The paths of the surrounding non-target pedestrians and their corresponding non-colliding trajectories are also shown (other various colors). The right panels depict the corresponding walking speed time series. Change in walking speed of the participant (pink), the target pedestrian (blue), and the non-target pedestrians (various colors) are shown over the entire run of the trial. The pink solid vertical line indicates the participant's response time (difference between the time of the response and the pedestrian offset). See text for a complete description of the individual behavioral profiles.

Video S1. Control participant
Video S2. CVI Participant 3
Video S3. CVI Participant 4
Video S4. CVI Participant 11