Evaluating lawful relationships in saccadic eye movements with simulated vision impairment: A proof-of-concept study

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The aim of this study was to examine the degree to which known lawful relationships in saccadic eye movements hold when visual acuity is artificially degraded. If lawful relationships still hold, then violations during the vision assessment could indicate that individuals are not performing with their maximum effort in an effort to exaggerate their impairment. Twelve healthy participants performed saccades between targets of different sizes and at different separations from each other. Each participant completed the task with habitual vision and with three levels of simulated impairment. Saccade duration and fixation dispersion both increased with target separation, irrespective of the simulated visual impairment (*R* values of 0.78 for duration and 0.27 for dispersion). Some eye movement measures retained lawful relationships with task constraints even when visual input was degraded. Although the present study does not assess the ability of these measures to detect intentional misrepresentation, the dependency of saccade duration and fixation dispersion on target separation under simulated vision impairment identifies them as candidate variables for future work aimed at improving confidence in vision assessments. Future work should examine whether saccade duration and fixation dispersion show the same lawful relationship in actual vision impairment.

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Introduction

When being fitted for glasses, it is usually in an individual's best interest to give their maximum effort on vision tests to allow the practitioner to optimize their vision as effectively as possible. During vision tests, such as when using a letter chart to measure visual acuity, clinicians typically rely on honest answers from the tested individuals (Bailey & Lovie-Kitchin, 2013). However, this subjectivity in vision testing allows individuals to misrepresent their vision as either better or worse than it actually is (Mann & Ravensbergen, 2018), introducing a margin of error that can lead to an inappropriate prescription or diagnosis. For example, if someone wishes to apply to become a pilot, where optimal vision is required, memorizing the sequence of letters on the chart could make the individual's vision appear better than it is. Conversely, when applying for monetary benefits available to persons with vision impairment, individuals might deliberately perform poorly on vision tests to make their vision seem worse than it is. This manipulation can lead to the unfair allocation of resources meant for genuinely impaired individuals. The susceptibility of testing to these dishonest responses highlights the need for new methods to safeguard the reliability of vision test outcomes (Deuble, Connick, Beckman, Abernethy, & Tweedy, 2016; Mann & Ravensbergen, 2018). Advanced technologies, such as eye-tracking systems, could be employed to ensure more accurate and less subjective assessments, reducing the potential for deception (Kanser, Bashem, Patrick, Hanks, & Rapport, 2020).

A similar problem with subjective vision testing arises in the realm of Paralympic sports, where athletes with vision impairment (VI) are typically classified into one of three sport classes to compete against others whose impairment has a similar impact on their sport performance. The aim of this classification system is to minimize the impact of the impairment on the outcome of the competition. By doing so, the classification system promotes inclusivity and equal opportunity among all athletes. However, the classification of athletes with VI, based on measures of visual acuity (VA) and the visual field, has been deemed controversial due to the subjective nature of those vision tests (Allen, Latham, Ravensbergen, Myint, & Mann, 2019; Mann & Ravensbergen, 2018; Mann, Tweedy, Jackson, & Vanlandewijck, 2021; Ravensbergen, Van Bree, Broekens, & Mann, 2018). Athletes with VI could misrepresent their vision during testing to be placed into a more beneficial class, increasing their chances of winning a gold medal. This form of cheating, termed *intentional misrepresentation*, is banned and penalized by the International Paralympic Committee. Even though athletes risk a life-long ban from international competition, reports from classification experts suggest that some athletes with VI are suspected of intentionally misrepresenting their impairment during vision testing (Allen et al., 2020; Krabben, Ravensbergen, Nakamoto, & Mann, 2019; Mann & Ravensbergen, 2018; Runswick, Ravensbergen, Allen, & Mann, 2021). For example, in a Delphi study by Allen et al. (2020), experts agreed that some track athletes who should be ineligible for competition are able to compete at major events due to intentional misrepresentation. Additionally, Powis and Macbeth (2020) found that, among VI football and cricket players, the lack of trust in the classification system leads to speculation and accusations of intentional misrepresentation by opposing players and even teammates. This ongoing problem undermines the integrity of the competition and creates an environment of distrust among athletes.

To tackle intentional misrepresentation on vision tests, Ravensbergen et al. (2018) conducted a study in which they investigated the variability of participants' responses to discriminate dishonest from honest answers on a vision test. In that study, participants were fitted with spectacles that simulated VI while they performed the Berkeley Rudimentary Vision Test (Bailey & Lovie-Kitchin, 2013), a test designed to measure VA in the presence of low vision. First, participants were asked to perform the vision test while answering honestly. Then, participants were taught how to misrepresent their vision on the test and were instructed to perform the test again, but this time to make their vision appear worse than it actually was. Participants with an actual VI also performed the vision test. Participants with healthy vision were successfully able to intentionally misrepresent their VA to be worse. However, Ravensbergen et al. (2018) were able to discern dishonest from honest answers based on the degree of variability in the responses of participants when testing the same level of VA using different sized stimuli at different distances. Significantly higher variability was found in the responses of participants in the intentional misrepresentation condition compared to responses in the honest condition, and when compared to participants with actual VI.

In their study, Ravensbergen et al. (2018) identified intentional misrepresentation by examining patterns in *subjective* participant responses that participants could control and adjust to imitate vision impairment. However, when attempting to develop a valid method to detect intentional misrepresentation on vision tests, it is desirable to rely on characteristics that are more *objective* and cannot be taught or mimicked.

Lawful movement behaviors might offer a solution to verify that vision tests are performed with maximum effort. An example of a lawful behavior is the speed–accuracy tradeoff described by Fitts' law, which was established in a reciprocal tapping task requiring participants to tap their finger between two targets as quickly and accurately as possible (Fitts, 1954). The difficulty of this tapping task is determined by the width of those two targets and their separation from each other (Fitts, 1954). Fitts (1954) demonstrated that the time to tap between the two targets was linearly related to the difficulty of the task. For example, small targets at a great distance resulted in longer movement times than larger targets at the same distance or the same targets at closer distances. Deuble et al. (2016) applied this principle in the manual tapping task to differentiate between participants who gave their maximum effort and those in an intentional misrepresentation group who were instructed to perform the task with 80% effort. The results from Deuble et al. (2016) illustrated that, in contrast to participants in the maximum effort group, the tapping movements from the intentional misrepresentation group did not conform to Fitts' law, thereby enabling a distinction to be made between those exerting maximum effort and those engaging in intentional misrepresentation. These findings highlight the potential to analyze lawful human movements to improve the accuracy of performance assessments.

Fitts' law, originally conceived to describe manual movements, has also been shown to apply to eye movements (Abrams, Meyer, & Kornblum, 1989; Al-Aidroos et al., 2007; Schuetz, Murdison, MacKenzie, & Zannoli, 2019; Wu, Kwon, & Kowler, 2010). In particular, sequences of saccades, which are fast eye movements that redirect gaze to new targets, have been shown to adhere to the principles of Fitts' law. It is important, however, to recognize key differences between saccadic and limb movements. Limb movements can be guided by visual and proprioceptive feedback acquired during the movement, whereas saccadic eye movements are generally too brief for visual feedback to influence the trajectory of the saccade mid-movement (Chen-Harris, Joiner, Ethier, Zee, & Shadmehr, 2008). As a result, additional corrective or secondary saccades may be necessary after that initial saccade to correct any landing errors.

Wu et al. (2010) examined the degree to which sequences of saccadic eye movements adhere to Fitts' law in a task where participants were required to move their eyes sequentially between four targets on a screen. They found the classical association between time taken and index of difficulty (ID) described by Fitts' law. This resulted from an increase in the frequency of corrective saccades with increased difficulty, as well as from the well-described association between saccade duration and target separation known as the *main sequence of saccades* (Collewijn & Tamminga, 1984; Gibaldi & Sabatini, 2021; Kowler & Blaser, 1995; Wu et al., 2010). Corrective saccades are secondary eye movements that correct for landing errors after an initial saccade. The number of secondary corrective saccades demonstrated an even stronger relationship with the ID than movement time as described in Fitts' law (Wu et al., 2010). This finding was later replicated by Schuetz et al. (2019). Both studies used a research-grade eye tracker with a high sampling rate (≥500 Hz) and tested participants over 1000s of trials. These findings suggest that lawful relationships between characteristics of saccades and fixations provide a potential means to assess the effort given during vision tests.

So far, the conformity of eye movements to Fitts' law has only been tested in individuals with healthy vision, so it remains unclear whether it would hold in cases where vision is compromised. This is an important point for any attempt to use such lawful behavior to discriminate intentional misrepresentation from genuine vision loss, because doing so only makes sense if the lawful behavior also holds when vision is impaired. One way to establish the association between impaired vision and eye movement behavior in a controlled manner is to do so using simulated vision impairment. Simulated VI has been used in a range of studies to examine the impact of vision loss on different visual behaviors (Cornelissen, Bruin, & Kooijman, 2005; Nuthmann, 2014). Similarly, full-field blur is commonly simulated to examine the impact of vision loss on motor performance to examine the minimum requirements for driving (Wood, Chaparro, Carberry, & Chu, 2010) and for inclusion in Paralympic sports (Allen, Latham, Mann, Ravensbergen, & Myint, 2016; Krabben et al., 2022; Krabben et al., 2021; Krabben, van der Kamp, & Mann, 2018). Simulated VI may prove to be similarly useful as a means of establishing conformity to lawful behavior in the presence of vision loss.

A vision test that is suitable for clinical use should ideally be practical and easy to administer. To replicate the findings by Wu et al. (2010), there are practical aspects in the study design that must be reconsidered. First, the participants in the Wu et al. (2010) study performed more than 1000 trials over multiple days: a time-consuming effort that is not realistic in a clinical setting. The minimum number of trials required to reliably observe Fitts' law is currently unknown, but a lesser number of trials is highly desirable. Second, the eye tracker used in Wu et al. (2010) was a research-grade instrument (EyeLink 1000; SR Research, Ottawa, ON, Canada) not typically used in clinical settings. Although it had a high sampling rate and good accuracy, this eye tracker is impractical for an application where the system should be portable and simple to use (e.g., no extensive calibration procedures), necessitating the exploration of more accessible and user-friendly alternatives. Practical adaptations would have to be made for the Fitts' law test to be suitable in clinical settings.

The aim of the present study was to assess the extent to which eye movements behave lawfully in the presence of simulated vision impairment. To achieve this aim, we simulated VI using blurring filters while participants made sequences of saccades between four targets that differed in configuration between trials. We adopted the paradigm introduced by Wu et al. (2010) but made some adaptations to make it more

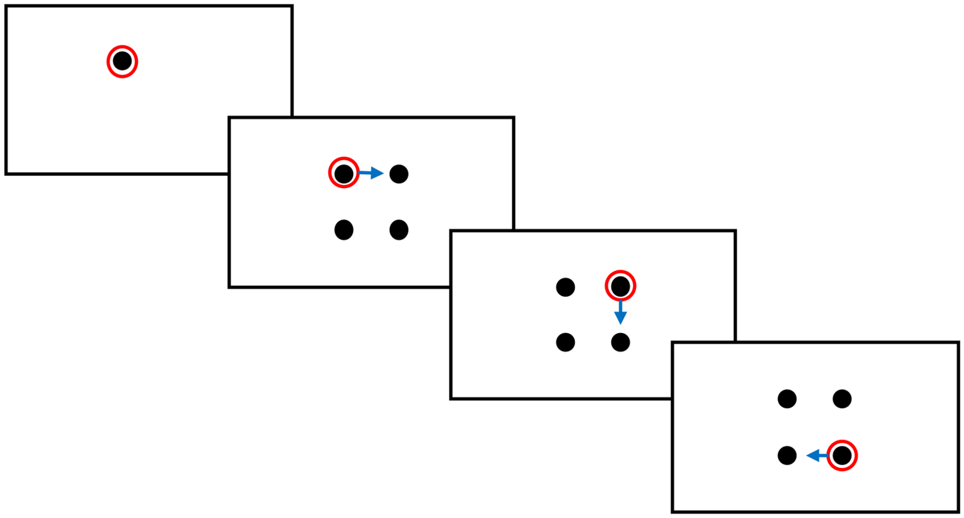

Figure 1. Representation of the paradigm to elicit saccadic eye movements. The target circles are black, red circles indicate the location of gaze, and the blue arrows indicate the direction of saccades. Participants completed three loops around the square (i.e., four targets) at a fast but comfortable pace.

clinically friendly. Specifically, we had fewer trials and used a mobile eye tracker. Based on the results, we assessed the conformity with lawful behavior when measuring different aspects of eye movement behavior. We expected the eye movement parameters to conform with lawful behavior in the habitual vision condition as previously observed in Wu et al. (2010). In this proof-of-concept study, our question was whether the conformity with lawful behavior would change in the presence of simulated vision impairment. Our ultimate goal is to outline a framework for the development of a tool to verify maximum effort on vision tests to increase the accuracy of vision assessments.

Methods

Participants

We recruited 12 participants (10 women) with an average age of 24.6 ± 3.3 years. Participants were required to have normal vision. Participants signed an informed consent form before participation. The study was approved by the Scientific and Ethical Review Board of the Vrije Universiteit Amsterdam and was conducted in accordance with the tenets of the Declaration of Helsinki with the informed consent of all participants.

Paradigm

The Fitts' law task for eye movements adopted in the present study was based on the paradigm used by Wu et al. (2010). It consisted of sequences of saccades between four circles located at each corner of an imaginary square (Figure 1). The target circles were black on a white background. Before each trial, one of the four target circles was displayed. Participants were instructed to look at this waiting target. When the participant was ready, the researcher pressed a button to start the trial. With the press of the button, the remaining circles appeared (Figure 1). Participants were instructed to move their eyes to look at each target circle in a clockwise direction at a rapid but comfortable pace (Wu et al., 2010). Participants were instructed to complete three loops around the square. The trial ended automatically when a custom-made online saccade detector identified 12 saccades. The online saccade detector used an adaptive (median-based) velocity threshold where potential saccades had to exceed this threshold for at least 15 ms (Schweitzer & Rolfs, 2020). This ensured that only large primary saccades were detected. Thresholds with shorter saccade duration (e.g., 8 ms) are typically used for the detection of secondary saccades (Ohl, Brandt, & Kliegl, 2011). This online saccade detector was only used for the stimulus display; a separate algorithm was used for the analysis of saccade metrics (see Data analysis).

Target configuration

Each block consisted of nine trials, with each trial displaying a different configuration of *target separation* (*S*; set to 255, 340, 425, or 510 min/arc) and *target diameter* (*D*; set to 60, 90, 120, 150, or 180 min/arc) (Figure 2). These two parameters determined the ID using the formula ID = $\log_2(2S/D)$. The IDs ranged

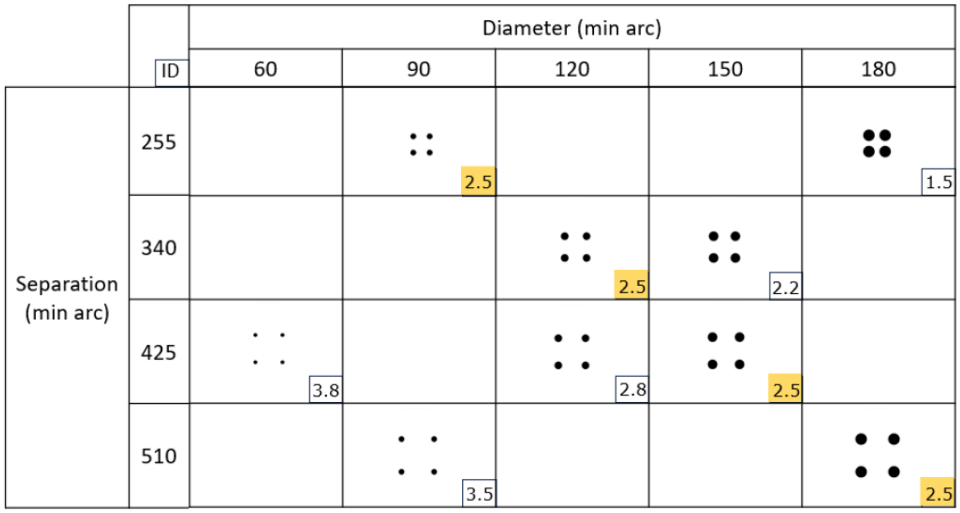

Figure 2. Overview of the different target configurations (not scaled) and resulting Fitts' indices of difficulty (IDs; lower right in each box where a stimulus was presented). Yellow indicates cases where the same ID was tested with different target configurations.

between 1.5 and 3.8, which enabled the assessment of the linear relationship between movement time (*MT*) and ID that Fitts' law prescribes (where *a* and *b* are empirically determined constants):

$$MT = a + b * log_2\left(\frac{2S}{D}\right)$$

We used a range of IDs similar to those of Wu et al. (2010), with the smallest ID (1.5) just above the critical ID of 1.41, above which saccadic eye movements are found to conform with Fitts' law (Schuetz et al., 2019). However, in our study, we used greater values for separation (*S*) and diameter (*D*) compared with previous studies because pilot testing showed that some targets with simulated VI became too small to see clearly or too smeared when the separation was small.

Similar to Deuble et al. (2016), we included four trials with different configurations of the same ID (ID = 2.5) using different combinations of separation and diameter (see yellow boxes in Figure 2). This inclusion allowed us to assess whether equivalent IDs resulted in comparable outcomes for the dependent variables, as prescribed by Fitts' law; this method could also be used as a measure of consistency of the participant's responses (Deuble et al., 2016). Moreover, it ensures that we could distinguish between relationships with ID and ones with only the diameter or separation. The trials were presented in a random order.

Apparatus

Eye movements were recorded using a Pupil Invisible mobile eye tracker (Pupil Labs GmbH, Berlin, Germany) with a sampling rate of 200 Hz. Without the need for calibration, the Pupil Invisible provides robust gaze estimations with an accuracy on the order of 4° of random error (Tonsen, Baumann, & Dierkes, 2020). Stimuli were presented on a laptop monitor (GT75VR 7RE Titan; Micro-Star International, New Taipei, Taiwan) with a resolution of 1920 × 1080 pixels and 120-Hz refresh rate. Stimuli were created in the open-source software package PsychoPy Builder. Python 3.8.10 was used to generate the stimuli and to control the experiment.

Simulated vision impairment

Vision impairment was simulated using Hampshire Frost (HF) filters (Lee Filters; Reading, UK). Light diffusion filters such as HF filters are usually applied in photography but have also been used to simulate VI (Goodman-Deane, Waller, Collins, & Clarkson, 2013). The HF filters vary in levels of the frost effect. For the simulation spectacles used in this study, the lowest level with product number HF258 was selected, also referred to as 1/8 strength. Different levels of simulated VI were achieved by layering the filters. The four vision conditions in this study were a baseline *habitual* condition with no VI, and *low VI*, *medium VI*, and *high VI* conditions that were simulated, respectively, using four, five, and six layers of the 1/8-strength HF filter. The VI conditions corresponded to visual acuities of, respectively, ~0.5, ~1.0, and ~1.3 logMAR. These values align with the definitions of low vision and blindness used by the World Health Organization for mild, moderate, and severe vision impairment, respectively, thus making them relevant for clinical application. The filters were fitted to simple three-dimensional (3D)-printed frames that covered the eyes and orbit. In the no VI condition, a clear film was fitted over the frame. The spectacles were fitted over the Pupil Invisible eye tracker.

Procedure

In a room lit only by artificial light, participants were seated 50 cm away from a monitor. Participants were then fitted with the eye tracker and performed four familiarization trials with habitual vision. After familiarization, the participants performed the task. The four vision conditions were alternated in a balanced fashion. In each vision condition, participants performed two blocks of nine trials. Thus, participants completed two trials per target configuration (Figure 2), 18 trials per condition, and 72 trials during the entire experiment. Following completion of the experiment, the participant's VA was measured in each of the four vision conditions. VA was measured in logMAR units using a standard Early Treatment Diabetic Retinopathy Study chart with tumbling Es. The total duration of the experiment was around 1 hour.

Data analysis

All data analyses were performed using custom-written Python 3.9 scripts. Gaze coordinates were converted from pixel units to degrees of visual angle using a conversion factor based on the screen dimensions and participant distance. Blinks were removed from the dataset. This did not affect the eye movement durations because the durations were computed from the original start and end time stamps, which were retained irrespective of blink removal. Experimental output from PsychoPy were aligned with the gaze data to accurately mark trial start and end times. A trial consisted of three loops around the set of four targets. A loop was defined as the moment of saccade onset when leaving the initial waiting target to the moment gaze left that target again. A loop always ended with a fixation on the top left target; therefore, a loop was expected to consist of four saccades and four fixations in a sequence. Loops that had fewer than four saccades and four fixations were excluded from data analysis.

Eye movements were analyzed using a combination of the Pupil Labs software and a custom-written Python script, similar to the procedure in Ghiani, Mann, and Brenner (2024). Blinks and fixations were automatically detected by the Pupil Labs software. We adopted the approach in Ghiani et al. (2024) for the detection of saccades. The gaze data were first smoothed by fitting the parameters of a second-order polynomial (Savitzky–Golay filter) to each moment in the data using least-squares regression within a window of 0.02 seconds. This gave us measures of the velocity and acceleration of the eyes at each moment. Velocity was given by the parameters of the first order of the polynomial fits for the horizontal and vertical gaze data. The overall velocity was obtained by squaring these derivatives and summing them. Acceleration was similarly obtained from the second-order parameters of the polynomial fits. We then ranked the velocity and acceleration values and converted these ranks into probabilities by dividing them by the total number of values and raising this fraction to the power of 6.58 (the value that makes the top 10% of the ranked velocities and accelerations have a probability greater than 0.5). Values above 0.5 were considered to be potential saccades. We refined this identification by ensuring that the orientation of the saccade did not change. To achieve this, we calculated the overall direction vector of the saccade by determining its horizontal and vertical components. We then computed the dot product between the segment vectors within the saccade and the overall direction vector. Any segment that deviated from the overall direction vector, as indicated by a negative dot product, was excluded from being classified as part of the saccade. Additionally, we ensured that consecutive saccades were separated by at least 50 ms. If two saccades were closer together, they were combined into one if the angular separation between their directions was less than 45°; otherwise, the smaller of the two saccades was discarded. Finally, we required the amplitude of the overall change in eye orientation during a saccade to be at least 1°. Saccades that did not meet this criterion were discarded.

Variables

We calculated four dependent variables: (a) segment time, (b) saccade duration, (c) dwell time, and (d) fixation dispersion. The segment time was calculated as the difference between the start and end times of each loop divided by four (four segments per loop). Each loop was then segmented into fixation and saccade events (Figure 3). For each saccade within a loop the saccade duration was calculated. The dwell time was the duration of the fixation.

We did not try to detect secondary saccades in our data given the limitations of the chosen mobile eye tracker. Instead, we required a displacement of at least 1° for a saccade to be considered as such, so that smaller saccades would simply contribute to the dispersion during fixations (Schuetz et al., 2019; Wu et al., 2010) between primary saccades. By quantifying the spatial dispersion of fixation during fixation, we obtained a measure for the consistency of the fixation position (Guadron, van Opstal, & Goossens, 2022), which we interpreted at least in part as a proxy for the occurrence of secondary saccades. For each fixation

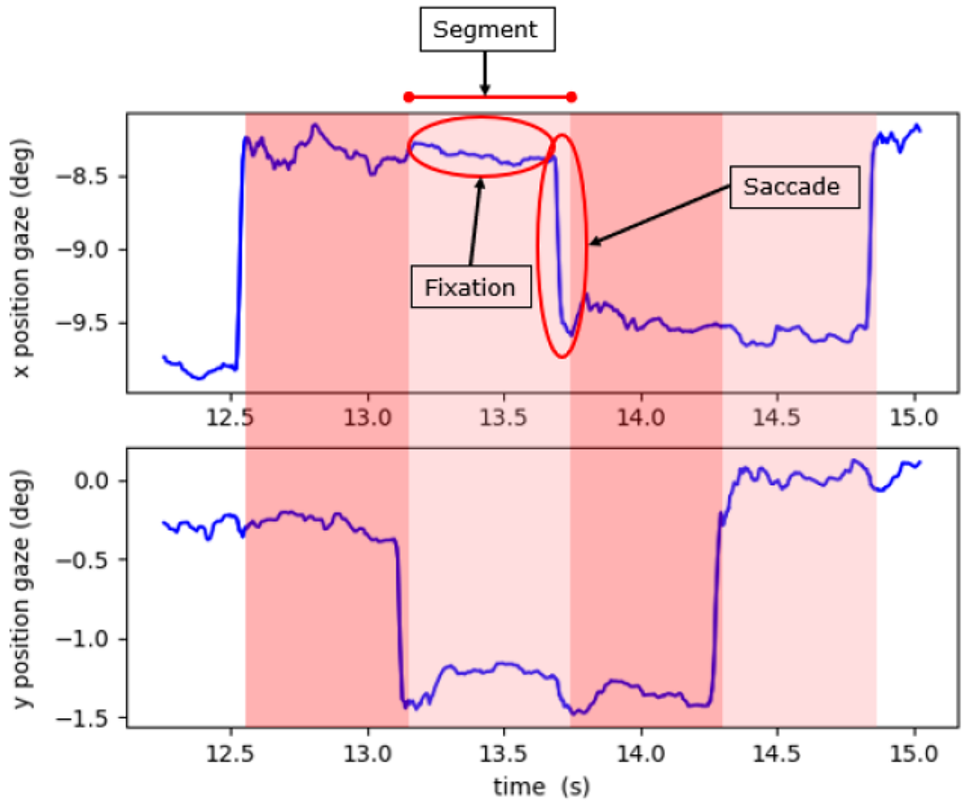

Figure 3. Sample of the gaze position in the *x* and *y* directions over time during a trial. The shaded areas represent four segments, each consisting of a saccade and the subsequent fixation. Average segment duration, dwell time, fixation dispersion, and saccade duration were derived from these data.

within a loop, we calculated the fixation dispersion as the bivariate contour ellipse area (BCEA); for examples of fixation locations during one session, see Figure 4. The BCEA was determined using Equation 1, where σ_h represents the standard deviation of gaze coordinates in the x direction, σ_v represents the standard deviation of gaze coordinates in the y direction, ρ represents the product–moment correlation of these two position components, and k is a constant (set at 3.079) representing the chosen probability area of 95% of eye positions during a trial (Murray et al., 2022).

$$BCEA = 2k\pi\sigma_h\sigma_v\left(1-\rho^2\right)^{1/2} \quad (1)$$

A filter method was required to avoid including trials where (a) participants skipped targets and/or (b) a clear distinction between fixations and saccades was difficult to make because participants skimmed the targets using a circular motion (this sometimes occurred when the separation of the targets was small and diameter large). Therefore, trials where dwell times were smaller than 100 ms or greater than 800 ms were discarded from data analysis. This threshold was very conservative: The dwell times in Wu et al. (2010) ranged from 280 ms to 480 ms. Similarly, trials where the fixation dispersion (BCEA) exceeded 1000 min/arc^2 were also removed. Outliers were removed using the interquartile range (IQR) method, where data points falling below 1.5 times the IQR from the first quartile or above 1.5 times the IQR from the third quartile were excluded. Independent variables were the ID, target separation (S), and target diameter (D).

Statistical analysis

To analyze conformity with Fitts' law, we performed linear regressions between the dependent and independent variables. This statistical approach allowed us to assess the strength and direction of the association between the variables. For each participant, a linear regression model was fitted in which the dependent variable was regressed onto a single independent variable. The strength of the association was quantified using the correlation coefficient (R), computed for each participant individually. In addition, an omnibus analysis was conducted using group-averaged data, from which a single correlation coefficient (R) was obtained. For each regression model, the slope coefficient (β),

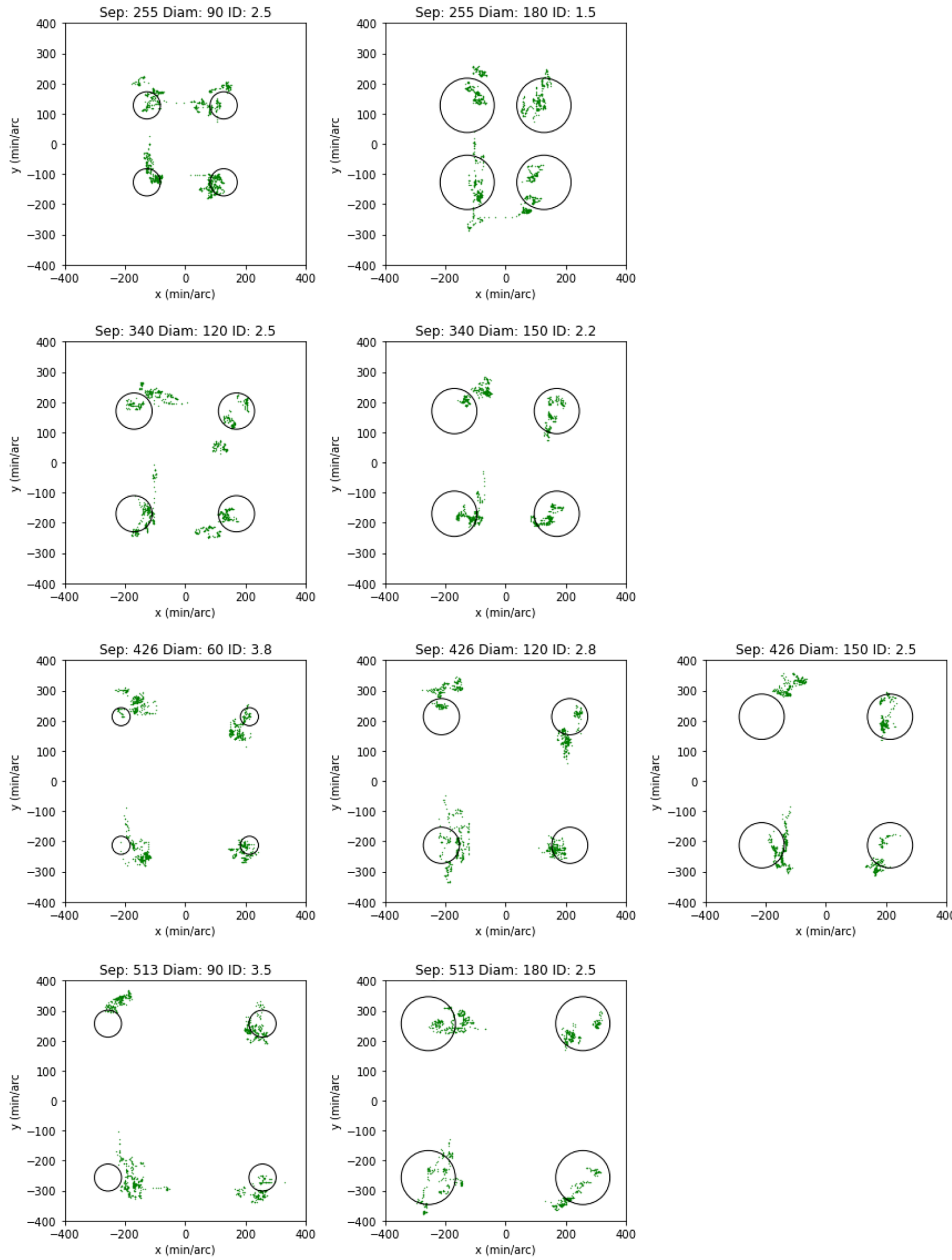

Figure 4. Example of the fixation dispersion for participant 11 superimposed on displays of four targets for each target separation and diameter, organized by separation. Data points are from a single trial, three loops, in the high VI condition.

along with its standard error and corresponding *p*-value, was used to assess the significance of the predictor. One-sample *t*-tests were conducted to determine if the resulting slope (β) and mean *R* values per condition were significantly different from zero. Additionally, to analyze the effects of the simulated VI conditions on conformity with Fitts' law, we employed repeated-measures analyses of variance (ANOVAs) to compare the *R* values across VI conditions. The Shapiro–Wilk test was performed within each condition to assess the normality of the *R* value distributions. Sphericity was tested with Mauchly's test, with Greenhouse–Geisser corrections applied if the assumption was violated. Then the repeated-measures ANOVA was conducted to evaluate the effect of condition on *R* values. Alpha for all statistical tests was set at 0.05.

Results

All 12 participants completed the experiment. Their average VA, without any simulated impairment, was –0.13 ± 0.13 logMAR. In the low VI, medium VI, and high VI conditions, VA was reduced on average to 0.55 ± 0.10, 1.03 ± 0.07, and 1.32 ± 0.08 logMAR, respectively. Each participant performed two trials per unique target configuration (nine configurations in total) (Figure 2) per vision condition (no VI, low VI, medium VI, high VI); each trial consisted of three loops around the targets. Therefore, each participant completed six loops per unique configuration per condition, 54 loops per condition, 216 loops in total. On average, 166 ± 31.8 loops per participant were analyzed. Loops were excluded if (a) participants skipped a target; (b) eye movements were circular rather than moving directly from target to target, making it algorithmically difficult to separate fixations from saccades; or (c) participants started with a predictive saccade before all targets were visible. Across conditions, the proportion of excluded loops increased with the higher levels of simulated blur (see Supplementary Figure S1); the average proportions of loops excluded were 18.9%, 18.5%, 22.6%, and 23.1% for the habitual vision, low VI, medium VI, and high VI conditions, respectively. A summary of key results for the eye movement variables can be found in Table 1.

Conformity with lawful behavior in habitual vision

Segment time

At the group level (based on averaged data), we did not find the expected positive linear relationship in the habitual vision condition between the ID and segment time (slope of the regression = 1.53; $R = 0.02$; $p = 0.88$) (Figure 5A). At the participant level, the average correlation between the ID and segment time across participants was 0.05 ± 0.57, which was not significantly different from zero ($p = 0.78$). There was also no association between either target separation or diameter and segment time: slope of the regression = 0.00 ($p = 0.99$) and slope of the regression = −0.06 ($p = 0.39$), respectively (Figures 6A and 6B). Thus, we could not replicate the effect of Fitts' law for segment time that was previously reported by Wu et al. (2010).

Saccade duration

The saccade duration increased with increasing ID (slope of regression = 4.24; $R = 0.78$, $p < 0.001$). Individual correlations ranged from 0.75 to 0.94, with an overall average of 0.84 (± 0.06), which was significantly different from zero ($p < 0.001$) (Figure 5B). Saccade duration increased with target separation (slope of regression = 0.05, $p < 0.001$), but it did not change with target diameter (slope of regression = −0.01, $p = 0.16$) (Figures 6C and 6D). Thus, the saccade duration was related to the target separation in accordance with the well-known *main sequence* of saccadic eye movements (Collewijn et al., 1988; Gibaldi et al., 2021; Wu et al., 2010).

Dwell times

Dwell times did not increase with increasing ID. At the group level, there was even a trend towards a negative slope for the regression (slope of regression = −6.19, $R = -0.08$, $p = 0.073$;) (Figure 5C). At the participant level, the average correlation was −0.20 (± 0.44) which was not significantly different from

Variable	Vision condition	Relationship ID (slope/R)	Relationship S (slope/R)	Relationship D (slope/R)
Segment time	Habitual	β = 1.53, R = 0.02	β = 0.00, R = 0.00	β = −0.06, R = −0.05
	Low VI	β = 4.34, R = 0.05	β = 0.01, R = 0.01	β = −0.12, R = −0.09
	Medium VI	β = 14.09, R = 0.15	β = 0.05, R = 0.07	β = −0.09, R = −0.05
	High VI	β = 11.39, R = 0.15	β = 0.05, R = 0.08	β = −0.16, R = −0.12
Saccade duration	Habitual	**β = 4.24, R =** 0.78**	**β = 0.05, R =** 0.92**	β = −0.01, R = −0.15
	Low VI	**β = 4.82, R =** 0.84**	**β = 0.05, R =** 0.95**	**β = −0.02, R = −0.46****
	Medium VI	**β = 4.59, R =** 0.81**	**β = 0.05, R =** 0.96**	β = 0.00, R = 0.01
	High VI	**β = 4.64, R =** 0.77**	**β = 0.05, R =** 0.91**	β = −0.01, R = −0.14
Dwell time	Habitual	β = −6.19, R = −0.08	β = −0.06, R = −0.10	β = 0.00, R = 0.00
	Low VI	β = 0.24, R = 0.00	β = −0.04, R = −0.07	β = −0.11, R = −0.08
	Medium VI	β = 5.88, R = 0.06	β = −0.01, R = −0.01	β = −0.09, R = −0.05
	High VI	β = 7.32, R = 0.10	β = −0.01, R = −0.01	β = −0.15, R = −0.11
Fixation dispersion	Habitual	**β = 34.32, R =** 0.27*	**β = 0.42, R =** 0.41*	β = 0.05, R = 0.03
	Low VI	β = 26.24, R = 0.19	β = 0.31, R = 0.27	β = −0.06, R = −0.02
	Medium VI	**β = 37.49, R =** 0.25*	**β = 0.36, R =** 0.34*	β = −0.03, R = −0.01
	High VI	**β = 31.36, R =** 0.24*	β = 0.22, R = 0.23	β = −0.24, R = −0.11

Table 1. Summary of key results for each eye movement variable. The values are averages across all participants' individual values. Bold font indicates a statistically significant slope (β). *$p < 0.05$; **$p < 0.001$.

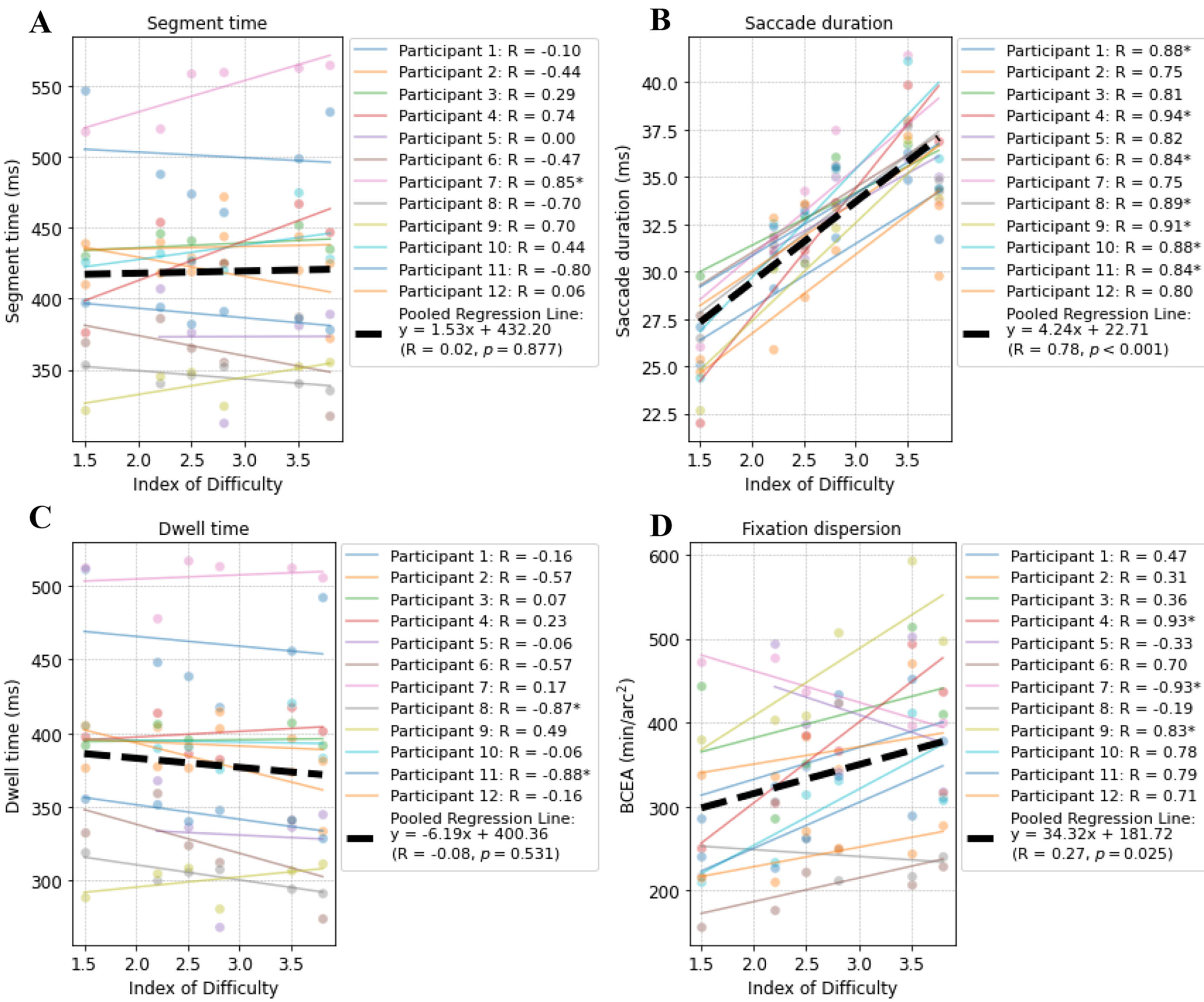

Figure 5. Linear regression between the dependent variables as a function of Index of Difficulty when viewing with habitual vision. (**A**) Regression for segment time. (**B**) Regression for saccade duration. (**C**) Regression for dwell time. (**D**) Regression for fixation dispersion. The black dashed line represents the average regression line. The correlation coefficient (R) for each participant's regression is presented in the legend with an asterisk indicating a significant linear regression.

zero ($p = 0.14$) (Figure 5C). Dwell times decreased with increasing target separation across participants (slope of regression $= -0.06$, $p = 0.027$). There was no systematic relationship with target diameter (slope of regression $= -0.01$, $p = 0.94$) (Figures 6E and 6F).

Fixation dispersion

Fixation dispersion increased with increasing ID (slope of regression $= 34.32$, $p = 0.025$; $R = 0.27$, $p = 0.026$) (Figure 5D). The average correlation was 0.37 $\pm$ 0.57, which was significantly different from zero ($p = 0.047$). Fixation dispersion increased with target separation (slope of regression $= 0.42$, $p = 0.004$) but not with target diameter (slope of regression $= 0.05$, $p = 0.85$) (Figures 6G and 6H). Therefore, the increase in fixation dispersion with Fitts' ID was not simply due to the bigger targets providing a greater surface on which to land. Rather, the variation was greater when the distance between the targets increased.

Overall, fixation duration and fixation dispersion increased in a manner consistent with Fitts' law. We could not replicate the effect of Fitts' law for segment

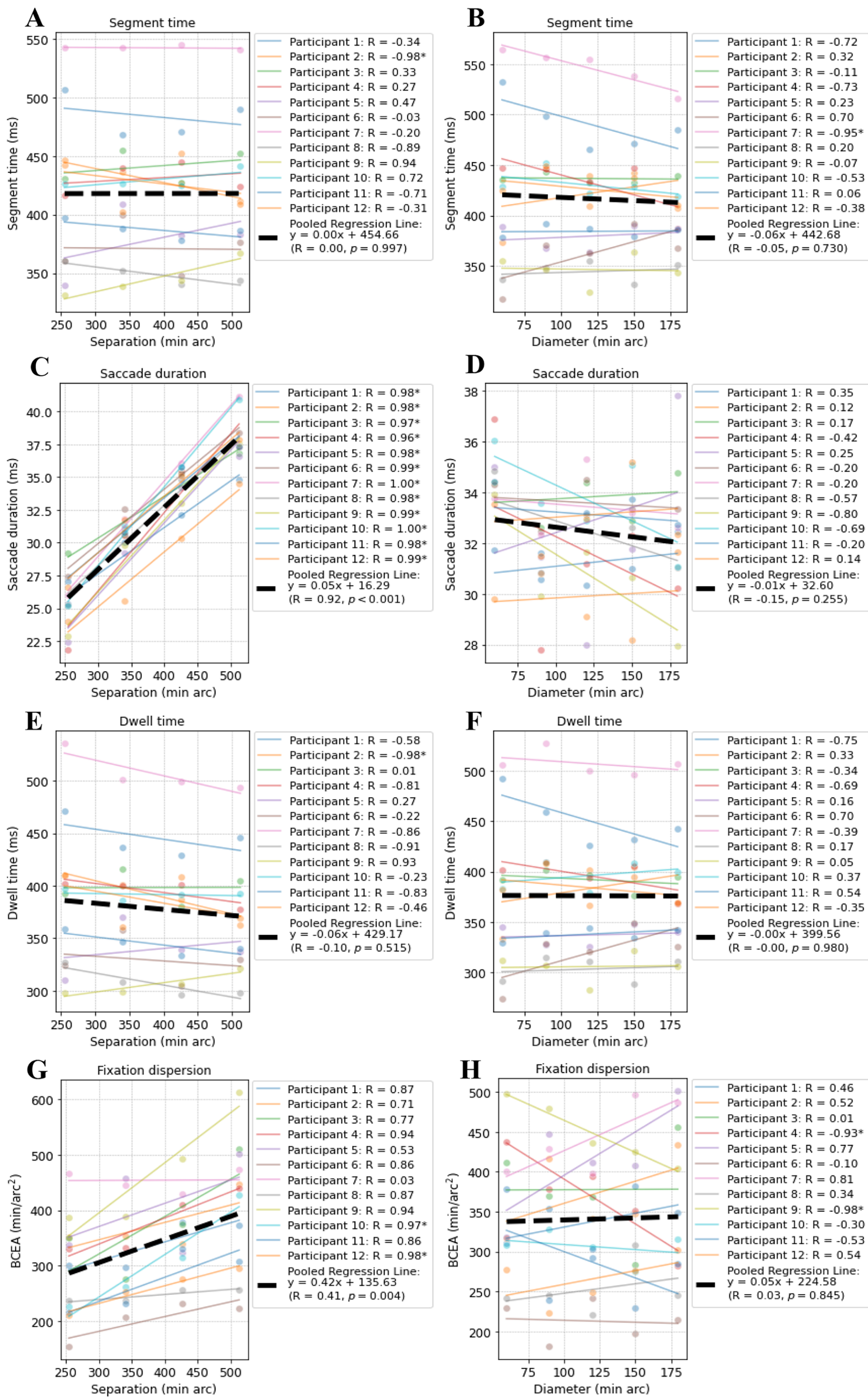

Figure 6. Linear regression for the dependent variables as a function of target separation (left panels) and target diameter (right panels) in the habitual vision conditions. (**A**, **B**) Regression for segment time. (**C**, **D**) Regression for saccade duration. (**E**, **F**) Regression for dwell time. (**G**, **H**) Regression for fixation dispersion. The black dotted line represents the average regression line across participants. The correlation coefficient (*R*) for each participant's regression is presented in the legend with an asterisk indicating a significant linear regression.

time when viewing with habitual vision that was previously observed in Wu et al. (2010).[1]

How the relationships change with simulated vision impairment

Having established that some variables scaled with ID and separation when viewing with habitual vision, we were next interested in the effect of simulated VI on that scaling. Figure 7 shows the R values for each of the four dependent variables and ID across each of the four vision conditions (see also Table 1).

Segment time

A repeated-measures ANOVA revealed a significant main effect of VI condition on the association between ID and segment time, $F(3, 24) = 3.07$, $p = 0.047$, $\eta_p^2 = 0.111$. The average R value was only significantly different from zero in the high VI condition ($p = 0.017$) (Figure 7A). There was no significant effect of VI condition on the association between segment time and separation, $F(3, 33) = 1.28$, $p = 0.30$, $\eta_p^2 = 0.083$, or diameter, $F(3, 30) = 0.59$, $p = 0.63$, $\eta_p^2 = 0.091$ (Figure 8A).

Saccade duration

A repeated-measures ANOVA revealed no effect of VI condition on the association between the ID and saccade duration, $F(3, 27) = 2.08$, $p = 0.13$, $\eta_p^2 = 0.100$ (Figure 7B), nor for the separation and saccade duration, $F(3, 21) = 0.78$, $p = 0.52$, $\eta_p^2 = 0.200$, or the diameter and saccade duration, $F(3, 24) = 3.05$, $p = 0.052$, $\eta_p^2 = 0.167$ (Figure 8B). For the ID and separation the R values were significantly different from zero in all VI conditions ($p < 0.001$) (Figure 7B, Table 1).

Dwell time

A repeated-measures ANOVA revealed a significant main effect of VI condition for the association between ID and dwell time, $F(3, 30) = 3.17$, $p = 0.038$, $\eta_p^2 = 0.091$ (Figure 7C). The average R value was only significantly different from zero in the high VI condition ($p = 0.024$). There was a main effect of VI condition on the association between separation and dwell time,

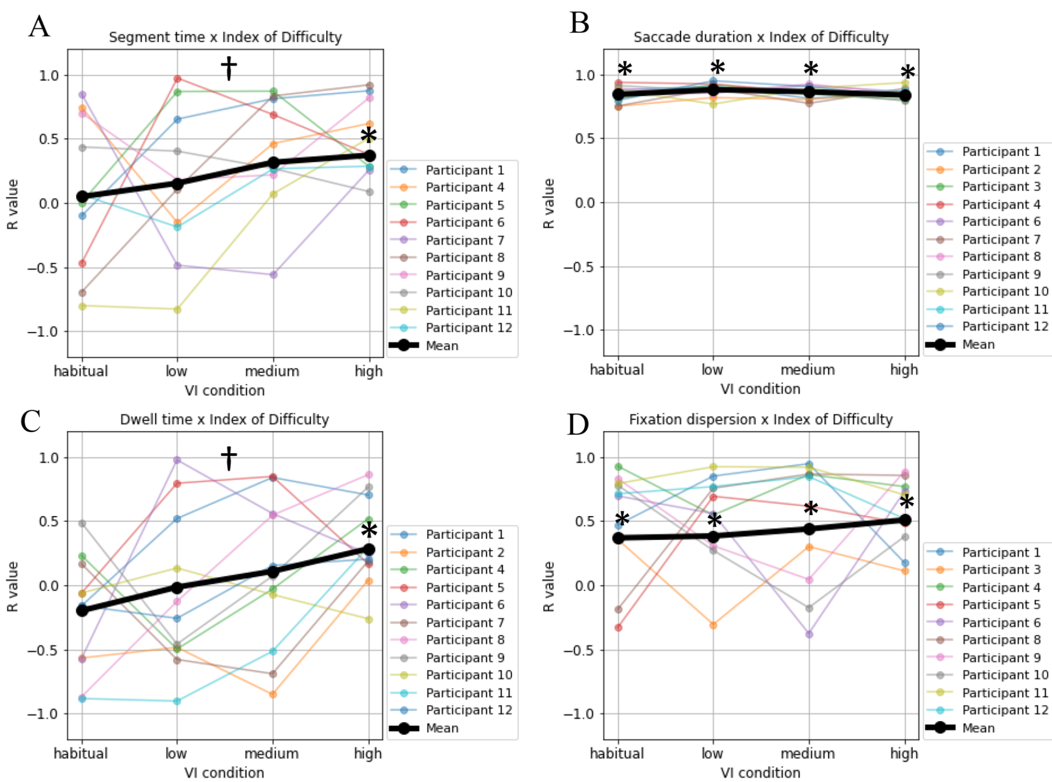

Figure 7. Correlation coefficients (R) for the dependent variables as a function of ID per participant for each of the four VI conditions. Average correlation is represented by the black line; a value significantly different from zero is indicated with an asterisk and a significant repeated-measures ANOVA is indicated with a dagger (†).

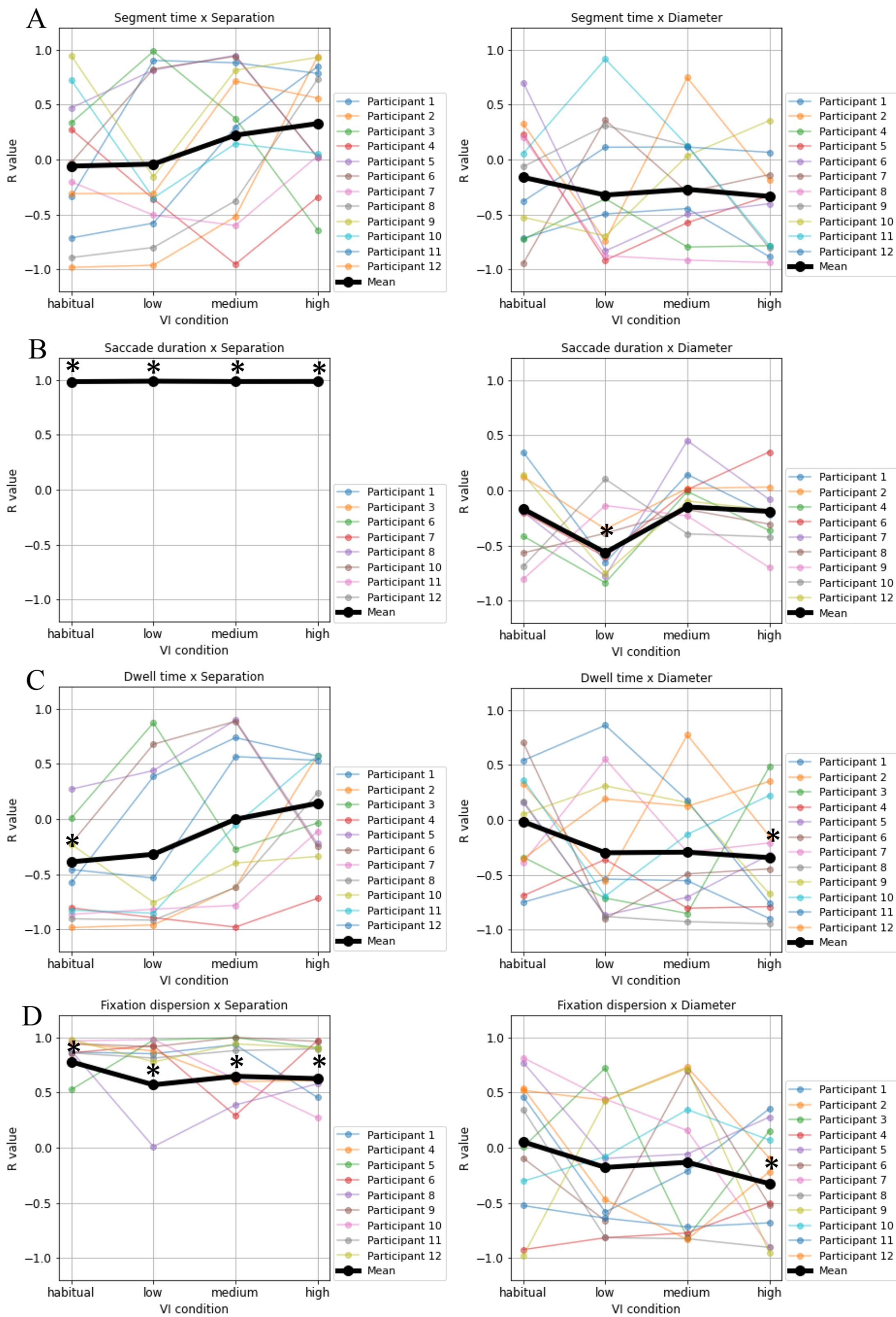

Figure 8. Correlation coefficients (*R*) for the dependent variables as a function of separation (left) and diameter (right) per participant for each of the four VI conditions. Average correlation is represented by the black line; a value significantly different from zero is indicated with an asterisk.

$F(3, 30) = 3.22$, $p = 0.036$, $\eta_p^2 = 0.091$. There was no effect of VI condition on the association between target diameter and dwell time, $F(3, 33) = 1.11$, $p = 0.36$, $\eta_p^2 = 0.083$. However, in contrast to the other conditions, in the high VI condition, the association between dwell time and target diameter was significantly below zero ($p = 0.034$).

Fixation dispersion

A repeated-measures ANOVA revealed no significant effect of VI condition on the association between ID and fixation dispersion, $F(3, 27) = 0.08$, $p = 0.97$, $\eta_p^2 = 0.100$ (Figure 7D), nor between target separation and fixation dispersion, $F(3, 24) = 0.67$, $p = 0.58$, $\eta_p^2 = 0.143$, or diameter and fixation dispersion, $F(3, 33) = 1.02$, $p = 0.40$ $\eta_p{}^2 = 0.083$ (Figure 8D). The average R values for the association between ID and fixation dispersion were significantly different from zero in all VI conditions (Figure 7D, Table 1).

Overall, saccade duration and fixation dispersion increased with target separation, not only in the habitual condition but also when faced with simulated vision impairment. Conversely, the results for segment time and dwell time did not show lawful relationships with target properties, neither when comparing across participants for the habitual condition nor when comparing participants' behavior for different levels of impairment.

Discussion

This proof-of-concept study provides a preliminary step in utilizing eye movements to improve confidence in vision assessments. We sought to test the applicability of lawful relationships between eye movements and target properties in the presence of simulated vision impairment. We recruited 12 healthy participants who were instructed to make sequences of saccades toward targets that differed in their separation and diameter, which together determined the ID. Adopting an easy-to-use experimental setup that involved increasing levels of blur to simulate VI, we examined the degree to which four eye movement variables (segment time, saccade duration, dwell time, and fixation dispersion) scaled to the task difficulty and whether that relationship was affected by simulated impairment. Results when viewing with habitual vision demonstrated that some variables scaled to the ID and others did not. Saccade duration and fixation dispersion scaled positively with the ID and in particular with target separation, suggesting that saccades took longer, and fixation positions became more varied with increasing target separation. The segment time did not show the linear relationship with ID that was reported previously (Murray et al., 2022; Schuetz et al., 2019), and there was no relationship with dwell time. Crucially, the lawful behavior found for the saccade duration and fixation dispersion was independent of the level of simulated impairment, suggesting that both aspects of behavior are robust to the effects of degraded vision. Collectively, these findings suggest that at least some measures of eye movement behavior may be candidates for inclusion in future assessment frameworks and test batteries aimed at improving confidence in vision assessments.

With habitual vision, two of the four dependent variables—saccade duration and fixation dispersion—scaled with the ID in a manner consistent with Fitts' law. Saccade duration, the time taken for a rapid, ballistic eye movement to move from one target to another, showed a particularly strong relationship, reflecting the well-established main sequence of saccades. This principle describes the linear dependency of saccade duration on amplitude, where larger saccades naturally require more time (Bahill, Clark, & Stark, 1975; Collewijn & Tamminga, 1984; Gibaldi & Sabatini, 2021; Wu et al., 2010). In our study, saccade duration demonstrated an almost perfect linear relationship with target separation ($R = 0.96$). This is responsible for the strong relationship with the ID ($R = 0.78$) that was also found in prior research (Guadron et al., 2022; Wu et al., 2010).

Fixation dispersion, which we used as a proxy for the landing errors that require secondary saccades, also scaled with the ID, albeit with a weaker linear relationship ($R = 0.27$). Previous studies have shown stronger associations, such as the dispersion (bivariate contour ellipse area) in Guadron et al. (2022) ($R = 0.77$) or secondary saccades in Wu et al. (2010) (average $R = 0.89$). Despite the lower R value, our results still indicate that there was a significant lawful relationship between target properties and fixation dispersion, suggesting its potential as a measure for maximum effort, albeit one that might require refinement to improve sensitivity. Individual variability in fixation dispersion was notable, with some participants even exhibiting a negative relationship with the ID. Such variability underscores the challenge of generalizing this metric across individuals and highlights the need for careful consideration when using such relationships as diagnostic tools for detecting submaximal effort. In a subsequent experiment, we increased the number of trials for three new participants, and here we observed a more convincing relationship between ID and fixation dispersion (average $R = 0.90$; range, 0.79–0.99) that aligned with the results from Wu et al. (2010). Thus, increasing the number of trials may improve the sensitivity of this measure.

Importantly, the overall R values for saccade duration and fixation dispersion were significant but not 1.0, which has important implications for clinical applications. While conformity to Fitts' law was evident, the degree of conformity for individual participants varied, reflecting both individual differences and inherent measurement noise. For detecting submaximal effort, it is critical to establish thresholds that can be used on a case-by-case basis, ensuring the measure's sensitivity to underperformance in individual participants rather than relying solely on group-level averages. This approach would minimize the risk of misclassification by considering individual-specific variability and ensuring that thresholds are sensitive enough to detect genuine submaximal effort without penalizing individuals unfairly for random fluctuations in their behavior or performance. Developing such thresholds would require robust validation across diverse (VI) populations and testing conditions to ensure reliability. Furthermore, the present study did not demonstrate that eye movement behavior can reliably identify intentional misrepresentation on vision tests.

Detecting intentional misrepresentation is a problem that may not be solved by a single metric or paradigm, and the present task is not designed to be immune to strategic manipulation. Rather, the contribution of this work is the identification of eye movement variables whose lawful relationship with task constraints remains stable under degraded visual input. In this context, conformity with lawful eye movement behavior can be interpreted as evidence of genuine effort, whereas failure to show such conformity does not suggest intentional misrepresentation but simply indicates that the test has not been passed and that further assessment may be warranted.

Fitts' law classically describes that there should be a positive linear relationship between movement times and the ID of the movement task (Fitts, 1954). With habitual vision, segment times in our study—that is, the collective time when moving from one target to another for the saccade and subsequent fixation—did not conform to Fitts' law. This finding is inconsistent with those from prior research examining eye movements and other movements more broadly (Schuetz et al., 2022; Wu et al., 2010).

Participants in our study only performed 18 trials per condition, or 72 trials in total, in contrast to on average 1363 trials over multiple sessions and days in Wu et al. (2010). To attempt to fully replicate the findings by Wu et al. (2010), we conducted a separate, identical experiment with three new participants to perform at least 1000 trials using our existing experimental design. From those results, we were able to replicate previous findings by Wu et al. (2010) for segment time. Where Wu et al. (2010) found an average R value of 0.66, we observed an almost identical association with an average R value of 0.68. Fitts' law is typically concerned with a speed–accuracy trade-off, but in our experiments we have shown that investigating Fitts' law is also a trade-off between methodological convenience (in terms of number of trials) and the strength of Fitts'-like associations.

Saccade duration and fixation dispersion were robust to increases in simulated impairment, with both variables consistently displaying significant correlations with target separation across all vision conditions irrespective of the level of blur. Additionally, repeated-measures ANOVAs did not reveal any significant change with increasing levels of VI for the two variables. The stability of these metrics is important, as it suggests that certain eye movement behaviors remain consistent despite the presence of simulated vision impairment. This result might be somewhat expected for saccade duration given that it is a saccade-related variable and that the oculomotor system is mostly unable to use visual feedback—regardless of whether or not this feedback is compromised—to adjust saccades in flight (Schuetz et al., 2019). In other words, saccades are preprogrammed and therefore variables related to saccades (saccade duration) might be those most expected to remain unaffected by VI.

A noticeable result of this study was that, with habitual vision, dwell times *decreased* with increasing target separation while remaining unaffected by target diameter. However, with medium or high levels of simulated VI, dwell times no longer decreased with increasing target separation; instead, they increased relative to dwell times in habitual vision. Additionally, with increasing target diameter, dwell times decreased, meaning that smaller targets (associated with higher ID) resulted in longer dwell times. As saccade duration remained relatively stable across conditions, the observed changes in dwell times directly influenced segment time (the sum of saccade duration and dwell time). With higher levels of blur, segment time similarly increased with the greater ID. This shift indicates that, under these conditions, participants required more time to initiate and complete their gaze shifts, making their movement patterns more predictable. The increase in dwell time might be an adaptation to facilitate more thorough information processing for each target to compensate for the reduced quality of visual information. This result may indicate that, with increasing levels of impairment, the task becomes more difficult, and therefore the limitations imposed by the target separation and diameter become more explicit. Conversely, it could indicate that, with habitual vision, the task was too easy and therefore target separation and diameter were not a limitation to performance. Together, these observations suggest that impaired vision does affect some aspects of task performance, in this case most likely the time necessary to prepare the subsequent eye movement, but that there are at least some aspects of the eye movement itself that are not affected (e.g., the saccadic duration itself).

Eye tracking has recently matured to become a viable tool for the assessment of visual function in individuals with VI (Nieboer, Ghiani, De Vries, Brenner, & Mann, 2023; Nieboer & Mann, 2025), and these assessments could benefit from the addition of the study of lawful relationships to enhance test reliability and detect submaximal effort. In Nieboer and Mann (2025), a test battery of eye movements was validated for assessing visual function in individuals with VI. The test battery included tests of fixation stability, smooth pursuit, saccades, free viewing, and visual search, and the battery was able to distinguish between individuals with different types of impairment and could predict reasonably well the performance on activities such as sports (Nieboer & Mann, 2025). Tests based on the established relationships found in the current study could be included in the test battery to help increase confidence in the results. We expect that, if participants perform the test battery with submaximal effort, then their results on those tests will not show the expected positive linear relationships, thus signalling reduced confidence in the overall outcome. In future work, there could be a study design where one group performs the test with maximum effort and the second group, who will be taught about the test and the principles involved, performs with submaximal effort. Confidence thresholds can then be developed to identify those participants performing with submaximal effort. Our results could ultimately increase the integrity of decisions based on visual function such as applications for (monetary) benefits for people with vision impairment, or for the classification of Paralympic athletes.

This study has some limitations that may impact the interpretation and generalizability of the findings. First, we used simulated blur rather than actual VI, which does not capture all aspects of real-world visual deficits, in particular impairments to peripheral vision or eye movements (Nieboer et al., 2023). We first wanted to demonstrate a proof of concept that at least some aspects of lawful behavior would hold under simulated impairment, and we think we have been successful in doing so. Further research is now needed to extend our findings to participants with actual VI and/or to employ gaze-contingent methods to simulate specific impairments to the visual field (e.g., central or peripheral vision loss) and to extend our findings to actual VI.

Another potential limitation of our study was the reasonably high proportion of loops that had to be excluded from the analyses. Loops were excluded in our study if participants skipped a target, produced circular eye movements, or started with a predictive saccade before the target appeared. We largely replicated the test paradigm introduced by Wu et al. (2010), and the average percentage of loops excluded we found in our study (18.9% of loops) was comparable to that in the study by Wu et al. (13.5%). The proportion of excluded loops did increase somewhat with higher levels of simulated impairment (low VI, 18.5%; medium VI, 22.6%; high VI, 23.1%), possibly because the poorer vision of the targets resulted in participants being more likely to deviate from the prescribed path, to make exploratory saccades, or to abandon loops mid-trajectory. The relatively high proportion of excluded loops does present a challenge, because it means that more trials must be performed to acquire sufficient data to provide a valid measure of an individual's saccadic behavior. In future iterations of the test, refinements might be necessary in the test stimuli used (i.e., by choosing the stimuli that minimize data loss) and/or in the algorithms used to detect the saccades and fixations to minimize loss. Confidence metrics from eye-tracking hardware might also help discriminate why data loss is high in some individuals, and an adaptive task that only presents certain stimuli (e.g., using gaze-contingent presentation of the next gaze target) may help reduce the predictability of our task, helping to reduce the loops that are excluded because of predictive eye movements or participants skipping forward to future targets rather than the next one.

To better understand how many loops are required to detect the expected linear relationship at the individual level, we conducted the follow-up study in which three new participants each completed more than 1000 loops. In the current study, participants completed 216 loops spread across four vision conditions, and, although group-level effects emerged, substantial individual variability was present. The follow-up dataset allowed us to examine when the relationship between our two strongest indicators of maximum effort—fixation dispersion and saccade duration as a function of target separation—first became significant for each participant. For fixation dispersion, which was the weaker indicator of the two in the current study, the regression reached significance at loop 157 (of 1391) for participant 1, loop 12 (of 1642) for participant 2, and loop 61 (of 1012) for participant 3. In contrast, for saccade duration, our strongest indicator, the regression was significant within the first 10 loops for all three participants. Importantly, the current study included multiple simulated blur conditions to assess sensitivity to changes in visual input; however, such manipulations would not be required in clinical use, where patients would perform the task under their habitual vision (which may already be compromised), meaning that only a single vision condition would be necessary. Taken together, these results show that, although group-level patterns were detectable with relatively few trials, establishing reliable relationships at the individual level benefits from increasing the number of loops. The follow-up study demonstrated that with higher trial counts the results become more consistent across individuals, with saccade duration demonstrating a reliably detectable relationship within very few loops and fixation dispersion requiring a larger number of loops but still achieving significance well within the range used in our extended testing.

This study provides initial insights into the potential of a test of eye movements to improve confidence in vision assessments, particularly in contexts where robust assessments of visual function are critical. We aimed to understand the impact of simulated VI on the conformity of eye movements with lawful behavior such as Fitts' law. Under habitual vision, the saccade duration and fixation dispersion scaled with the ID, and the relationship between each and the ID remained robust under simulated VI. This suggests that those two variables at least may be promising indicators of maximum effort that are unaffected by degraded vision. These metrics provide a basis for further exploring metrics to safeguard vision assessments. Integrating this approach into established eye movement tests could enhance the accuracy of visual function assessments, particularly in fields where objective measures are essential, such as Paralympic classification and decisions regarding allocation of benefits for individuals with vision impairment. Future work should focus on validating these findings in individuals with VI, and examining whether these metrics can help identify intentional misrepresentation. Ultimately, a practical law-based tool could become a useful test for vision assessments, enhancing the reliability of decisions based on visual function.

Keywords: eye movements, vision assessment, Fitts' law, simulated vision impairment, saccades

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Footnote

[1]We conducted a second experiment replicating our setup and paradigm but recruited three new participants who performed 1125 trials with habitual vision to replicate the number of trials in the study by Wu et al. (2010). In this second experiment, we obtained the following results for the dependent variables regressed over the ID:

- Segment time—Average $R = 0.68 \pm 0.22$; significant for one out of three participants
- Saccade duration—Average $R = 0.87 \pm 0.01$; significant for all participants
- Dwell time—Average $R = 0.38 \pm 0.46$; not significant for any participant
- Fixation dispersion—Average $R = 0.90 \pm 0.10$; significant for 2 out of 3 participants.

We found Fitts' law–like associations between index of difficulty and segment time, saccade duration, and fixation dispersion, but not dwell time. With this second experiment, it is shown that by increasing the number of trials, the strength of the associations (R-value) also increased for all eye movement variables except saccade duration (which has been consistently high in all analyses).

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