TITLE [*Max words*: 50; *Currently*: **17**]
Using an open-source tablet perimeter (Eyecatcher) as a rapid triage measure in a glaucoma clinic waiting area.

RUNNING HEAD
Eyecatcher: An open-source tablet perimeter.

PRECIS [*Max words*: 35; *Currently*: **35**]
We describe a novel 'triage' perimeter ("Eyecatcher"), which combines low-cost eye-tracking technology with a portable tablet computer. We assess its feasibility as a pragmatic means of identifying the presence or absence of visual field abnormalities.

PRECIS [120 chars for Twitter]
Evaluating a portable, hands-free tablet perimeter in a glaucoma clinic waiting area #Eyecatcher @crabblab

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SUPPLEMENTAL MATERIAL
This article contains one video and two text items, to appear as additional online-only material. Supplemental text is included at the end of the present manuscript. The following video should appear online only: *SupplementalVideoS1_EyecatcherTestSequence.wmv* (caption: "Example test sequence").

MEETING PRESENTATION
Elements of this work were presented at ARVO 2019.

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No conflicting relationship exists for any author

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P.R. Jones, None; **D. Lindfield**, Allergan (honorarium and consultancy), Alcon, Novartis, Thea, EndoOptiks, Optotek (honorarium); **D.P. Crabb**, Roche (unrestricted funding), Allergan (unrestricted funding and speaker fee), Santen, THEA and Bayer (speaker fee), Centervue (consultancy).

AUTHOR CONTRIBUTION STATEMENT
P.R.J., D.L., and D.P.C conceived the designed the study. P.R.J. developed the test materials and collected the data. P.R.J. analysed the data and wrote the manuscript. All the authors contributed toward finalising the draft.

ABSTRACT [*Max words*: 250; *Currently*: **250**]

Background: Glaucoma services are under unprecedented pressure. The UK Healthcare Safety Investigation Branch recently called for new ways to identify glaucoma patients most at risk of developing sight loss, and of filtering-out false-positive referrals. Here we evaluate the feasibility of one such technology, "Eyecatcher": a free, tablet-based 'triage' perimeter, designed to be used unsupervised directly within clinic waiting areas. It does not require a button or headrest: patients are simply required to look at fixed-luminance dots as they appear.

Methods: Seventy-seven people were tested twice using Eyecatcher (one eye only) while waiting for a routine appointment in a UK glaucoma clinic. The sample included individuals with an established diagnosis of glaucoma, and false-positive new referrals (no visual field or optic nerve abnormalities). No attempts were made to control the testing environment. Patients wore their own glasses and received minimal task instructions.

Results: Eyecatcher was fast (median: 2.5 mins), produced results in good agreement with standard automated perimetry (SAP), and was rated as more enjoyable, less tiring, and easier to perform than SAP ($P<0.001$). It exhibited good separation (ROC=0.97) between eyes with advanced field loss (Mean Deviation <-6 dB) and those within normal limits (MD > -2 dB). And it was able to flag two thirds of false-positive referrals as functionally normal. However, eight people (10%) failed to complete the test twice, and reasons for this limitation are also discussed.

Conclusions: Tablet-based eye-movement perimetry could potentially provide a pragmatic way of triaging busy glaucoma clinics (flagging high-risk patients and possible false-referrals).

KEY WORDS: *glaucoma; visual fields; static perimetry; eye-movements; triage*

1. INTRODUCTION

British glaucoma services are under strain from an ageing population and more cautious referral policies[1]. There is an increasing backlog of appointments[2], and it is believed that around twenty patients a month suffer severe avoidable sight loss as a result of appointment delays[3]. A recent report by the UK Healthcare Safety Investigation Branch (HSIB) found that the lack of timely monitoring is putting patient safety at risk and recommended "better, smarter ways of working … to maximise the current capacity" [4]. The HSIB report highlighted, in particular, the need to develop new ways to: (1) identify and prioritise patients most at risk of developing sight loss, and (2) filter-out false-positive referrals (~40% of new referrals, in the UK[5,6] and mainland Europe[7,8]).

The great majority of patients likely to experience statutory blindness within their lifetime, already have marked visual field [VF] loss at first presentation to a glaucoma clinic[9] (i.e., a Mean Deviation [MD] worse than −6 dB in at least one eye). A healthy VF is also a key indicator that a patient has been referred in error. A simple VF assessment --- conducted immediately as the patient enters the clinic, or as they sit in the waiting room --- could therefore be one possible step towards achieving HSIB's goals of prioritising high-risk patients and flagging-up likely false-positive referrals.

Standard automated perimetry [SAP] is inappropriate for this 'rapid triage' role, as it requires specialist equipment and a trained technician. Thus, it is not unknown for patients to wait several hours for an SAP exam: a potential bottle-beck in patient flow in itself. Our vision is therefore not to replace SAP, but to complement it with a simpler 'triage' assessment, that is inexpensive, and could be used directly in glaucoma waiting rooms.

A VF triage assessment would not be a like-for-like replacement for SAP. The examination might be simpler and less detailed: with fewer test locations, and/or fixed-luminance stimuli. Instead, it should focus on identifying individuals with no measurable visual field loss, and highlighting those individuals most at risk of developing sight loss within their lifetime (e.g., younger adults with worse than MD -6 dB loss in one eye[9]). Crucially, however, a triage exam must not add to the existing burden faced by patients and clinicians. In practical terms, this means a test that --- unlike SAP[10] --- is extremely easy to administer, does not require bulky or expensive equipment, and does not require a trained operator or dedicated space in which to run.

We recently proposed one such test[11]: Eyecatcher, an open-source eye-movement perimeter that combines the portability of an inexpensive tablet computer[12–18], with the ease and comfort afforded

by modern eye- and head-tracking technologies[19–23]. In brief, the patient sits in front of an ordinary tablet screen, and is simply asked to look at anything they see appear (a largely reflexive response, present from birth[24]). Unlike traditional SAP, there is no response button or central fixation target. Instead, the eye-tracker determines where on the screen to present a given stimulus in order to stimulate a particular retinal location (i.e., relative to the current point of fixation). The eye-tracker then analyses eye-movements to determine whether the user saw the stimulus. The use of head-tracking also removes the need for head restraints, since the size and location of the stimulus is scaled dynamically to compensate for viewing distance. In short, Eyecatcher removes headrests, fixation spots and response buttons from perimetry, and as a result delivers a more portable, intuitive, and comfortable test, and one which can be run autonomously, since, unlike SAP, it does not require an operator to explain the test or monitor fixation.

We have shown previously that Eyecatcher provides VF data concordant with SAP when applied to a small, self-selecting sample of research participants[12]. Here we examined the feasibility of applying it in a busy glaucoma clinic; and in particular, whether it can be used as a rapid triage test to identify high-risk individuals (MD < -6 dB), and false-positive referrals (no visual field or optic nerve abnormalities).

2. METHODS

2.1. Participants

Participants were 77 adults, sampled opportunistically from individuals attending routine appointments at the glaucoma clinic of Royal Surrey County Hospital: A secondary care centre in south-east England. No attempt was made to select participants, and the only inclusion requirement was the capacity to provide written informed consent. The cohort included both returning patients with an established diagnosis, and 11 new referrals (Table I). This study was approved by the NHS Health Research Authority (IRAS ID: #230440) and was conducted in accordance with the Declaration of Helsinki.

2.2. Eyecatcher

The version of Eyecatcher (v2.0) used in the present study is an updated version of that described previously[12]. In brief, participants sat approximately 55 cm in front of a Windows Surface Pro 4 tablet computer (Microsoft, Redmond, Washington, U.S.), and were asked simply to "look at anything you see" (Figure 1A). On each trial, an inexpensive (~£100) clip-on eye-tracker (Tobii EyeX; Tobii Technology, Stockholm, Sweden) was used to position fixed-luminance stimuli relative to the current estimated point of fixation (no central fixation marker), and to determine whether the participant looked towards the target (no response button; Figure 1D). Viewing distance was not strictly controlled, but was monitored in real-time by the eye-tracker, and was used to scale the size and location of the stimulus as required, prior to each presentation. Patients were not supervised during testing, although the experimenter typically remained nearby (performing paperwork).

Stimuli were Goldmann III targets, 6 dB more intense than the expected threshold of normal adult at each grid location[25] (NB: this value was not adjusted for patient age, but could be in future). The -6 dB cutoff was chosen since 90% of patients at risk of statutory blindness within their lifetime have an MD worse than −6 dB at presentation[9]. For other clinical applications (e.g., case-finding or home monitoring) a different cutoff may be more appropriate. Additional technical details are given in Supplemental Text. The complete source code for Eyecatcher is available online at https://github.com/petejonze/Eyecatcher, and is free for non-commercial use.

The output from Eyecatcher is a retinotopic map, giving the probability of seeing the target at 22 paracentral locations (Figure 1B), including 11 of the most informative points from the 24-2 grid, as identified by Wang & Henson (2013)[26]. These 22 values were interpolated to provide a continuous probability map (Figure 1C), ranging from bright green ('always seen') to bright red ('never seen', VF

loss). A summary measure was computed by mean-averaging the probability-of-seeing values across the 22 locations. The resultant metric, "Mean Hit Rate", is a number between 0 and 1 that reflects the amount of 'greenness' in the VF plot. It is potentially comparable to the HFA's summary measure of VF loss: mean deviation (MD).

[Figure 1 About Here]

Figure 1. Eyecatcher. ***(A)*** Apparatus and stimuli. The tablet screen measured 26cm x 17.3cm (26.6° x 17.9° when viewed at 55 cm). The eye-tracker is magnetically attached to the base of the tablet. ***(B)*** Test Grid, in degrees visual angle ***(C)*** Example Output. Green areas indicated hits (target looked at). Red areas indicate misses (target not looked at). ***(D)*** Example test sequence. On each trial a single fixed-intensity light spot was presented, and the computer determines whether or not an eye-movement was made towards it. Note that stimuli were presented relative to the current point of fixation, and so could appear at any screen location throughout the course of the test. See Supplemental Video S1 for example test sequence.

2.3. Procedure

In each participant, only a single eye was tested. The test eye was randomly selected, and the fellow eye patched with a cotton swab (monocular viewing). Testing was performed twice consecutively (same eye), to assess test-retest repeatability. To reflect the fact that Eyecatcher is intended as a rapid and easy-to-administer assay, no refractive correction was provided. However, patients were asked to wear their own near-vision spectacles if available.

Testing took place in whichever space was available that would not disturb other patients (typically an office or consulting room adjacent to the main clinic waiting area). Lights were dimmed where possible, but no attempt was made to maintain a precise light level. No attempt was made to prevent patients or members of staff walking past during testing, and this occurred regularly.

Following the test, participants were given a short usability questionnaire, containing five Likert statements (e.g., "I found the test easy to perform"). Participants answered each question twice: once for Eyecatcher, and once for SAP.

All testing took part in a single session: generally while the patient waited for SAP or their subsequent consultation. A minority of individuals had received a mydriatic (tropicamide) by the time they performed Eyecatcher. However, this was not systematically recorded.

As part of their scheduled appointment, all participants underwent a full visual assessment by the local clinical team, including a monocular SAP assessment (24-2; SITA Fast) using the Humphrey Field Analyzer (Carl Zeiss Meditec, CA, USA).

2.4. Analysis

Data are described using non-parametric statistics (e.g., medians), with 95% confidence intervals computed using bootstrapping (N = 20,000; bias-corrected and accelerated method).

3. RESULTS

Seventy-seven participants (33 female) were recruited, including 11 new referrals (see Table 1 for breakdown). All 11 new referrals were judged by their treating physician to be false-positive referrals, with no visual field or optic nerve abnormalities. No individuals were excluded from the study, and only one additional individual was approached, but declined to participate in the study. We were therefore able to obtain a relatively representative sample of 'typical' clinic attendees. Median (IQR) age was 70 (59--77) years.

Participants		
Diagnosis	*N* Eyes	
	all	new referrals only
Primary Open Angle Glaucoma	44	0
Normal Tension Glaucoma	5	0
Primary Angle Closure (PAC)	2	0
PAC w/ Glaucoma	2	0
Ocular Hypertension (OHT)	7	1
OHT w/ borderline Glaucoma	3	0
Pigmentary Glaucoma	1	0
Other (complex cases)	3	0
Nil abnormal	10	10
Total (all participants)	**77**	**11**

Table 1. Breakdown of diagnoses for the full cohort (N=77, including new referrals), and for the subset of individuals who were new referrals to the clinic (N=11).

3.1. Completion Rate

Sixty-nine patients (90%) completed Eyecatcher twice without difficulty, but 8 did not. One early failure was due to a technical error. The remaining 7 failures were due to the eye-tracking hardware being unable to track the eye reliably (returning no data, or data that was sporadic and imprecise). The cause of these eye-tracking failures could not be conclusively established. However, of these seven cases: five may have been due to recent ophthalmic interventions (four had recently undergone cataract surgery, one had complex pathology due to radiotherapy for cavernous meningioma). One was believed due to dry eyes (a symptom of an oral steroid, taken for a non-ophthalmic condition). One eye could not be tracked for reasons unknown: the only distinctive feature was pupil dilation with Tropicamide with associated blurred vision, though other dilated eyes were tracked without problem.

3.2. Accuracy (concordance with HFA)

Figure 2 shows individual data for 22 patients, including all 11 new referrals (Figure 2A), and 11 randomly-selected follow-up patients with established diagnoses of glaucoma (Figure 2B). By inspection, it can be seen that Eyecatcher was often able to localize scotomas with reasonable spatial

precision. Note, for example, the nasal step in ID12, and the inferior temporal scotoma in ID22. In some cases, however, Eyecatcher did appear to underestimate (ID19) or mislocalise (ID17) the loss.

As shown in Figure 3, there was good association (*Spearman Correlation: r* = 0.78; $p < 0.001$) between the overall summary measures from Eyecatcher (mean hit rate) and SAP (MD). Crucially, no individuals with substantial field loss were found to be visually normal by Eyecatcher (Figure 3, upper-left region), although some individuals with a healthy visual field did score poorly (Figure 3, bottom-right region).

[Figure 2 About Here **]**

Figure 2. Individual VF assessments for **(*A*)** all 11 new referrals (none of whom is believed to have glaucoma) and **(*B*)** 11 randomly-selected follow-up patients (all with established diagnosis of glaucoma). In each case, the HFA greyscale is given on the left and the two corresponding Eyecatcher heatmaps on the right (Eyecatcher was performed twice). Red markers highlight regions of the HFA where loss was greater than the magnitude of Eyecatcher stimulus (– 6 dB). If concordance between the two tests was perfect, then red areas in the HFA should appear as red areas on the Eyecatcher heatmap. Note that new referral ID 9 was non-glaucomatous, but was a cataract patient with a generalized loss of sensitivity across the visual field (MD = -5.6 dB).

[Figure 3 About Here **]**

Figure 3. Agreement in overall sensitivity between Eyecatcher (Mean Hit-Rate) vs. SAP (HFA Mean Deviation; dB). Each data-point represents a single test/eye from a single patient. Each patient completed Eyecatcher twice, and the data from each run is given separately (circles, squares). The solid line shows the line of best fit (polynomial spline fit). Any data points falling in the top left shaded region would be considered a false-negative result (good performance on Eyecatcher, despite substantial field loss).

3.3. Sensitivity and Specificity

Eyecatcher demonstrated good separation between eyes with moderate or advanced field loss (< -6 MD; N = 24) and those with a VF within normal limits (> -2 dB; N = 22), with an area under the receiver operating characteristic (AUROC) of 0.97 {CI_{95}: 0.94, 0.99} (see Supplemental Figure S1).

In terms of identifying unnecessary ('false-positive') new referrals to the clinic, we took a mean hit rate of 0.7 as an arbitrary cut off point for 'good' performance. Eight of 11 new referrals (all of whom were judged to be visually normal) scored above 0.7 (Sensitivity: 73%), while 0% of assessments from eyes with MD < -6 dB scored below 0.7 (Specificity: 100%).

3.4. Test-retest Reliability

Figure 4 shows Eyecatcher's test-retest repeatability. The 95% Coefficient of Repeatability (CoR_{95}) for Mean Hit Rate was 0.19 (19% of the test's dynamic range. Note that Eyecatcher measures the % of fixed-intensity points seen, rather than luminance detection thresholds). For comparison, in SAP, the conventional summary metric MD has been shown previously[27] to have a CoR_{95} of ~1.4 dB (~4% of range) at 0 dB MD, increasing to ~5.2 dB (~17% of range) at -30 dB MD. Thus, Eyecatcher was less

reliable (repeatable) than conventional SAP. There was no indication of systematic learning or fatigue across the two test runs.

[Figure 4 About Here]

Figure 4. Bland-Altman plot, showing test-retest repeatability for Eyecatcher (mean hit rate). Grey shaded regions show 95% confidence intervals for the mean. Dashed red lines indicate the 95% limits of agreement.

3.5. Test Duration

Median duration {$CI_{95\%}$} was 2.5 mins {2.4, 2.7} for Eyecatcher, and 3.5 {3.3, 4.1} mins for SAP (SITA Fast). This difference was significant (*Pairwise t-test*: $P \ll 0.001$), though note that SAP tested more locations, and measured thresholds. Also note that these times do not include additional overheads, such as the time taken to seat/position the participant, explain the test, or apply refractive correction; all of which were minimal for Eyecatcher, but can be substantial for SAP.

3.6. Usability

Participants rated Eyecatcher more enjoyable, easier to perform, less tiring, and less hard to concentrate on than SAP (4 *Pairwise t-tests*: all $P < 0.001$). There was no difference in task-comprehension ($P = 0.419$), which was near ceiling for both tests (see Supplemental Figure S2). There were no significant difference in patients' perceptions of Eyecatcher between new referrals and follow-up patients (5 *between-subject t-tests*: all $P > 0.05$).

4. DISCUSSION

This study considered the feasibility of using a portable, automated, eye-movement perimeter (Eyecatcher) to perform a rapid assay of VF loss in a real-world clinical setting. In particular, we examined whether it could be used as a preliminary 'triage test' for clinic waiting areas, to identify high-risk individuals (eyes with substantial VF loss: MD < -6 dB), and likely false-positive referrals (no visual field or optic nerve abnormalities).

Eyecatcher demonstrated good separation (AUROC = 0.97) between eyes with moderate-to-advanced VF loss (< -6 dB MD) versus those within normal limits (> -2 dB MD). This is encouraging, as the vast majority of individuals expected to go blind within their lifetime already exhibit moderate or worse VF loss at presentation[9]. Eyecatcher might therefore be used to flag up these individuals as 'high risk'. In terms of false-positive new referrals, 68% were correctly identified as having no substantial VF loss (MD > -6 dB), while crucially 0% of patients with established VF loss (MD < -6 dB) were incorrectly flagged as healthy. In practice, this might translate to two thirds of new referrals being granted an expedited discharge, while the remaining 1-in-3 patients would continue to wait to perform SAP as before. Taken together, the results suggest that Eyecatcher --- though still in early development --- exhibits potential promise as a way of prioritising patients, and filtering-out false-positive referrals, as called for by the HSIB (see *Introduction*).

Crucially, Eyecatcher requires minimal clinical resources, being a fully automated, unsupervised procedure that does not require expensive, specialist equipment or a dedicated testing space (e.g., no precise control of lighting, with patients wearing their own glasses as available). Patients also exhibited no difficulties comprehending what to do, despite minimal instructions ("look at anything you see"). The present data would likely have been cleaner and more impressive if we had used 'research-grade' protocols and equipment. However, such a test would be of little practical value as a real-world tool. As it was, it is possible to imagine rows of autonomous Eyecatcher-type devices installed in waiting rooms, or at the entrance to clinic – potentially using the same or similar hardware as current 'self-service' check-in system.

Eyecatcher was fast (~2.5 mins, including eye-tracker calibration), but the HFA (SITA Fast) made detailed threshold measurements, at more locations, in only ~3.5 mins, and new HFA algorithms may be even faster than Eyecatcher[28]. The goal was not, however, to create a maximally fast test, but one that is easy, intuitive, and fast enough to run unsupervised. These 'human factors' were reflected in the fact that patients rated Eyecatcher easier and less tiring than traditional, button-press perimetry, and stands in stark contrast to SAP, where a technician must be continuously present to explain the

test and monitor performance, and where even well practiced patients can find the test challenging[10] or confusing.

4.1. Limitations

This study was intended only as an initial feasibility assessment. It should not be taken as a formal evaluation of diagnostic accuracy, which would require a standardized protocol[29], and a much larger, multi-centre, prospective sample. A more comprehensive evaluation would also consider economic utility, and might examine test performance with different target intensities (fixed here at -6 dB). A smaller value might, for example, be beneficial if attempting to detect very early signs of glaucoma.

Regarding Eyecatcher itself, the test is limited in three main ways. First, several patients (9%) could not complete the test due to the hardware being unable to track their eyes reliably. In five cases the difficulties were likely caused by recent ophthalmic interventions (e.g., cataract surgery). Such patients will be 'in the system' already and are not the sorts of 'new referrals' that a rapid triage test such as Eyecatcher would be primarily targeted at. In the other two cases, however, the cause of the problem was either unknown (*N*=1), or appeared to be due to a side effect of a common medication (dry eyes; *N*=1). These failures are concerning, but it is hoped that reliability of low-cost eye-tracking technologies will improve in time. In the meantime, such individuals could simply continue to perform SAP (as they do currently), or could perform a button-press version of Eyecatcher (see Supplemental Text).

Second, since Eyecatcher requires an eye-movement response, it is unable to test central vision (e.g., the most central point was ±3° horizontal, ±6° vertical). This is unfortunate, since central vision is increasingly thought to be affected in early glaucoma[30]. More precise eye-tracking, or an alternative response measure, would be required if wanting to assess more central VF locations in future.

Third, when it came to identifying false-positive referrals, Eyecatcher exhibited high specificity (identifying 100% of eyes with MD < -6 dB), but limited sensitivity (only 68% of false-positive referrals were correctly identified as having no measurable field loss). This asymmetry was by design. In triage, the cost of misidentifying a diseased eye as healthy (whereafter a new patient might be wrongly discharged) is far greater than the cost of misidentifying a healthy eye as diseased (whereafter the patient would simply continue to wait for a more detailed assessment). Eyecatcher therefore required multiple negative responses to register a location as 'missed', while a single positive response was sufficient to classify a location as 'seen' (see Supplemental Text). Sensitivity might be improved through improved test design or longer test durations. However, the practical corollary is that the

Eyecatcher, as it is currently, shows promise as a triage measure, but would make for a poor general screening device (i.e., where both high sensitivity and specificity are required).

4.2. Further Possible Applications & Future Work

Eyecatcher was intended as a rapid triage measure for use in clinics. Given its portability and ease of use, however, Eyecatcher might also be useful in situations that require testing outside of traditional eye clinics (e.g., home-monitoring, domiciliary services, or case-finding in developing rural communities), or for performing VF assessments in individuals with limited physical or cognitive abilities (e.g., infants or stroke patients). For people interested in adapting or developing Eyecatcher further, we have made all of the source code freely available online (see *Methods*).

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