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Fixation termination during visual search with simulated visual impairments

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ABSTRACT
Everyday tasks such as finding a friend in a crowd rely on efficient visual search, a process that heavily relies on efficiently executing eye movements. But how does our visual system adapt eye movement behavior when visual input is degraded? Here, we investigated whether eye movement behaviour during visual search adjusts to simulated visual impairments. Participants performed a visual search task whilst their eye movement behaviour was recorded under three conditions: normal vision (control), monocular vision (with an eye patch over the dominant eye), and low-contrast vision (with reduced stimulus contrast). Overall, we found that search was slowed under conditions of simulated visual impairments, with increases in RTs, fixation durations, and time to fixate the target compared with a control condition. Our results provide further support for mixed-control models of fixation termination and have implications for understanding eye movement control under visual impairments.

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Visual search; fixation termination; lag-2 revisits; visual impairment

Visual search tasks involve looking for specific target objects among distractor objects (for a review, see Wolfe, 2020) and require eye movements to enable us to find those targets or determine their absence (for a review, see Godwin et al., 2021). Eye movements are the most common of all of our behaviours, and we make around 5 eye movements every waking second (Rayner, 2009). Eye movement behaviour consists of *fixations* – brief periods when visual input is acquired – and *saccades*, which are rapid movements that shift our point of gaze during which visual input is attenuated. During a fixation, the visual system must decide when to terminate a fixation and initiate a saccade. Here, we examined fixation termination during visual search, with a focus on how fixation termination is influenced by degrading the visual input using simulated visual impairments.

Our experiment taps into an important debate regarding the process by which fixations are terminated during search. Accounts of fixation termination have taken three overall approaches to explain how and when fixations are terminated. *Direct control* accounts (Rayner, 1978) hold that fixations are terminated under the exclusive control of online cognitive processing. Under these accounts, the visual system waits until it has fully processed the visual information about the object(s) currently being fixated before initiating saccadic programming (the planning of the next eye movement). *Indirect control* accounts (Engel, 1977; Vaughan, 1982) argue instead that fixations are terminated at a fixed time point regardless of any ongoing cognitive processing. Here, saccadic programming begins once a deadline timer has been triggered. Finally, there are *mixed-control* accounts which assume that saccadic programming begins before the object(s) being fixated are fully examined (Rayner & Pollatsek, 1981). Under these accounts, the oculomotor system balances the need for efficient online cognitive processing of the object(s) being fixated against the need to minimise "dead time" that would arise under direct control accounts. This dead time would arise when the oculomotor system waits for the processing of object(s) being fixated to be completed and only then begins programming a saccade (Vaughan, 1982).

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Although some early work suggested that fixations are terminated under an indirect control approach (Hooge & Erkelens, 1996, 1998), these early attempts at examining fixation duration control in search were limited by their low sample size. In these studies, only a handful of participants were recruited, and no formal statistical analyses were conducted. Since that time, a far larger evidence base has emerged in support of a mixed-control account of fixation termination during visual search. For example, fixation durations increase as task difficulty increases. Conversely, as searchers gain experience with a stimulus set and/or search task – which makes the task easier and more straightforward to complete – fixation durations decrease (for a review, see Donnelly et al., 2019). Even within a single search trial, fixation durations increase when searchers fixate objects that are more similar to the target compared to those objects that are less similar to the target (Becker, 2011; Reingold & Glaholt, 2014). Moreover, fixation durations increase as a search trial progresses (Godwin et al., 2014; Over et al., 2007). These examples all suggest that there is no one set fixation duration, as posited instead by indirect control accounts (Henderson & Pierce, 2008; Henderson & Smith, 2009; McCarley et al., 2003).

Further evidence for a mixed-control process governing fixation durations during visual search comes from studies that have examined lag-2 revisits. As noted above, these arise when the eyes fixate an object twice in a tight sequence (Peterson et al., 2001). This sequence of fixations has been referred to as a lag-2 revisit since there is a lag of 2 fixations between the initial visit and the revisit. They occur because the initial visit to an object was too brief to enable full identification of the object and have been described by a "miss + realization account" wherein a searcher fails to fully identify the object upon first fixation, realises this, and then rapidly returns to it. The rapid return to the original object is more likely to occur when the initial object is the target. Following up on this finding, Godwin et al. (2017), found that lag-2 rates could be modulated by changing participants' expectations that any given object would be the target. This was achieved by presenting participants with displays that contained many objects similar to the target or few objects similar to the target. Since a target was present on every trial, having many target-similar objects in a trial meant that the probability of any one object being the target was low; when there were few target-similar objects in a trial, the probability of any one object being the target was much higher. In their results, Godwin et al. (2017). found that lag-2 revisit rates increased when the probability of any one object being the target was lower, suggesting that searchers were taking this probability into account to determine fixation termination. Taken together, as already noted, there is substantial evidence now that fixation durations during visual search are governed via a mixed process.

The current study

The goal of the current study was to better understand fixation termination during visual search by using simulated visual impairments. At the core, the issue of fixation termination under a mixed control process is what can be referred to as a "Goldilocks problem": fixations must not be terminated too early or too late, but at the "right" time (whatever that may be). If a fixation is terminated too early, then insufficient information may be acquired from the object to fully identify it. When this happens, a lag-2 revisit may occur, as described above. For target objects, if a lag-2 is not triggered, the searcher may simply fail to detect the target altogether. This problem of fixating targets and not detecting them has long been discussed in the literature (Nodine & Kundel, 1987), and in recent times has been referred to as a failure of identification (Cain et al., 2013; Godwin et al., 2015, 2016, 2020; Godwin et al., 2017; Hout et al., 2015) as well as a "look but fail to see' error" (Wolfe et al., 2022). Conversely, when a fixation is terminated too late, then time will be wasted fixating an object from which no further information is needed to be acquired from.

Under a mixed control account, the time to terminate fixations is determined by a top-down prediction regarding the object that is being fixated. In Godwin et al.'s (2017) study of lag-2 revisits, as noted above, changing the likelihood that objects will be the target influenced the lag-2 revisit rate, yet they found no evidence that fixation durations were influenced by this likelihood. From this we can conclude that, when faced with the Goldilocks problem of fixation termination, the oculomotor system prefers to hold fixation durations low and accept the potential penalty of increased revisits and occasional errors. But is this the case for the other factor known to influence fixation termination – namely, the difficulty of object examination – as well? Here, we addressed this question by holding the likelihood of each object being the target constant and instead introducing different forms of simulated visual impairments. We achieved this by (1) asking participants to wear an eye patch over their dominant eye and (2) reducing the contrast of the objects in the displays that they were searching. These manipulations were not meant to perfectly reproduce specific impairments, but rather to broadly capture general patterns of impairment. The eye patch simulated the loss of an eye, or situations such as amblyopia therapy in which children are required to wear a patch for extended periods to strengthen the weaker eye (Papageorgiou et al., 2019). The reduced contrast condition simulated contrast sensitivity loss, a feature of almost all visual disorders, from cataracts to macular degeneration, glaucoma, optic neuropathy, and many others (Wolkstein et al., 1980).

From a practical perspective, conducting further study into the effects of simulated visual impairments upon eye movement behaviour offers the ability to further understand under-examined real-world problems. Visual loss can occur in many forms (Bourne et al., 2013). During development and into adulthood, conditions such as congenital cataracts, amblyopia and strabismus can cause significant visual impairments. In aging populations, diseases such as age-related macular degeneration, glaucoma, and cataracts can also deteriorate visual function. Additionally, eye trauma or injury, infections, and malignancies can even result in the loss of an entire eye. All of these situations are likely to impact activities of daily living (Jones et al., 2019; Lamoureux et al., 2004; Senger et al., 2017; West et al., 2002), including visual search. However, although impairments in search performance are well-documented in situations of visual loss (Smith et al., 2011), it is challenging to pinpoint the mechanisms through which these impairments originate. For instance, it is known that low contrast increases both search times and fixation durations (Näsänen et al., 2001), but nothing is known on whether this also affects lag-2 revisits. Simulating hemianopia (the loss of a whole visual hemifield in both eyes) also leads to impaired search accuracy and reaction times, and even though participants develop more efficient eye movement behaviours over time, surprisingly performance remains suboptimal even with practice (Nowakowska et al., 2016, 2019; Tant et al., 2002). The effects of losing an eye are also largely unknown, although it is well established that binocular visual sensitivity is generally better than monocular sensitivity due to binocular summation (Campbell & Green, 1965).

Predictions

Our primary analyses focused on the eye movement behaviour of participants as they searched the displays in the different conditions. We examined a series of measures relating to the target and distractor objects themselves. First, we examined the single fixation duration on distractor objects. Single fixation durations are the "cleanest" measure of information processing of an object since they reflect the total time required to process that object without needing to make any additional fixations or revisits (Godwin et al., 2021). We predicted that single fixation durations would increase relative to the control condition in both of our conditions of simulated visual impairment, given past research that has also found that fixation durations increase when the difficulty of identifying objects increases (Rayner, 2009).

Next, we examined measures relating to the target object only. The first of these was the time taken to fixate the target. Search is known to be guided towards objects that are similar to the target (Wolfe, 2021), with fixations more likely to land on target-similar objects (Godwin et al., 2014; Menneer et al., 2012). Generally, when search becomes more difficult, the time to fixate targets increases (e.g. see Godwin et al., 2017; Godwin et al., 2020), so we anticipated here that, under conditions of degraded visual input, the time to fixate targets would increase relative to the control condition because the fixation durations in general had also increased. We then examined the verification time for target objects. This is measured as the time between first fixating the target and responding (Cain et al., 2013; Godwin et al., 2021; Nodine & Kundel, 1987). As such, verification time charts the ability of searchers to identify a target once fixated. Verification times increase when search becomes more difficult (Cain et al., 2013; Godwin et al., 2021; Nodine & Kundel, 1987), so we again anticipated that this measure would increase under conditions of degraded visual input.

Finally, we examined lag-2 revisit rates for both target objects and distractors. Here, we expected that these lag-2 revisit rates would increase for the simulated visual impairment conditions compared to the control condition, in a similar vein to those reported by Godwin et al. (2017). The idea here is that the search system generally takes a conservative approach and even if fixation durations are increased, they may not be increased by a sufficient degree as to preclude the need to return to objects after first leaving them.

Method

Participants

We did not conduct a power analysis in advance of this study. Instead, we utilised a combination of previous lag-2 revisit and visual search literature to inform our stopping rules regarding participant counts and experiment length (e.g. Godwin et al., 2014, 2017). With this in mind, we had a target of ∼15–20 participants for this study.

As such, we recruited a total of 21 undergraduate psychology students from the University of Southampton. Participants reported normal or corrected-to-normal vision in order for them to take part. Participation was optional, and participants did not receive compensation.

Apparatus

Participants' eye movements were recorded using an Eyelink 1000 Plus, running at 1000 Hz (i.e. 1 sample per millisecond). The eye tracker was calibrated using the system's native nine-point calibration routine. Calibrations were only accepted with an average error of less than 0.5° of visual angle and a maximum error of less than 1° of visual angle on each individual point of calibration. Drift correction preceded each trial, and calibration was repeated after each break (every 50 trials), as well as at the start of each experimental block.

Stimuli were presented on a gamma-corrected 25-inch BenQ XL2540 K monitor with a 100 Hz refresh rate and a resolution of 1920 × 1080 pixels. Participants were seated 90 cm from the screen, in a dimly lit room, with their head stabilised using a chinrest. Responses were made using the computer keyboard. The experiment was programmed in SR Research Experiment Builder, with additional code written in Python.

Stimuli

The stimuli consisted of one target object, the letter "T", and one distractor object, the letter "L". All target and distractor objects were 1° of visual angle in height and width, and presented in the same colour, orange (rgb: 255, 100, 60), on a white background (Weber contrast = − 0.77). In the low-contrast condition, we rescaled the luminance contrast of the stimuli to 10% of the original (rgb: 255, 245, 244, Weber contrast = − 0.08).

For each trial, a total of 16 stimuli were displayed, containing one target object and 15 distractor objects. Stimuli were randomly placed on a 5 × 4 virtual grid before being allocated a position up to 20 pixels (0.36° of visual angle) away from their start point on the x and y planes. Distractor objects were randomly rotated by 0°, 90°, 180°, or 270° increments. Target objects were oriented at either 90°, with the "T" stem pointing rightward (50% of trials), or 270°, with the "T" stem pointing leftward (50% of trials).

Design and procedure

This study used a repeated measures design. The experiment consisted of three conditions comprising a *Control*, a *Monocular* condition, and a *Low-contrast* condition. Each condition involved 100 trials, and 25 practice trials beforehand. To test the participant's dominant eye, a hole in card was used and therefore we could track the non-dominant eye. To do this, participants were asked to look at a distant object through a small hole in a card with both eyes open and closing each eye in turn. The dominant eye was determined as the eye that kept the object in view when the other was closed (Rice et al., 2008).

At the beginning of data collection, each participant was positioned in the chinrest, the non-dominant eye was selected, and a nine-point calibration procedure was conducted. Once the first calibration was successful, practice trials commenced. Participants were tasked with searching for a target ("T") amongst a set of distractors ("L") and respond using "X" or "N" on the keyboard regarding whether the "T" was pointing to the left or right. Prior to each trial, a reminder of the target was presented at the centre of the display. Once the participant had fixated the object for 500 ms, the main images for the trial began. This approach was taken to ensure that participants began each trial fixating the centre of the display (Godwin et al., 2021).

The three experimental conditions were completed by each participant in three separate blocks each lasting around 20-30 min. Blocks were counterbalanced across participants using a Latin square design. In the control condition, the trials were presented without any visual degradation, and the task was identical to the practice trials. The monocular condition was identical to the control condition aside from the fact that participants wore an eyepatch (a sterile, nonwoven, adhesive eye pad) over their dominant eye, so that only their non-dominant eye could see the stimuli. Participants rested for 5 min before and after the monocular condition to adjust to their surroundings wearing and not wearing the eyepatch. In the low-contrast condition, the task was identical to the control condition, except the stimuli were presented at 10% luminance contrast comparted to the control condition. A breakdown of the trial structure/sequence can be found in Figure 1.

Results

Data cleaning

Raw eye tracking data were processed and cleaned using the EyeTrackR R package (Godwin & Muhl-Richardson, 2019) for R (R Development Core Team, 2024). Of a total 99,025 fixations that were recorded, 1,845 (1.9%) were removed due to being less than 250 ms or greater than 1200 ms, leaving a total number of 97,180 fixations in the final dataset. We treated fixations as having landed on a given object if they fell within 2.5° of visual angle of that object. Response time and eye movement analyses were based upon correct-response trials only.

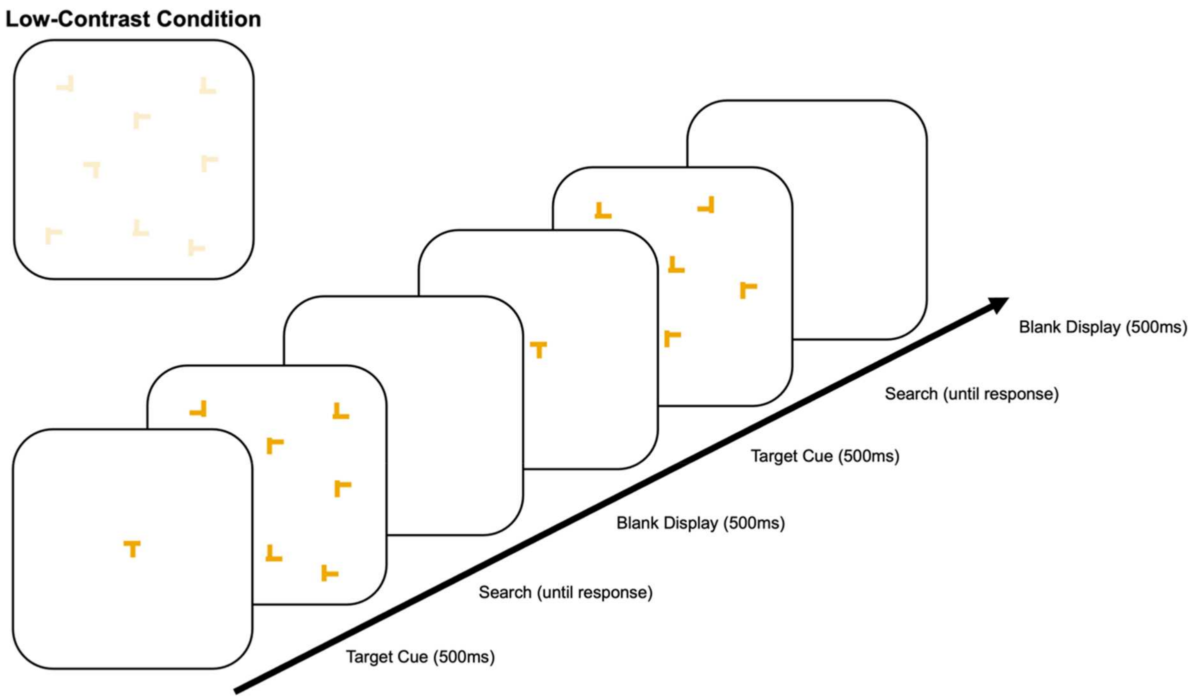

Figure 1. Example trial sequence.

Note: Figure depicts typical trial sequences for our search tasks. The experiment consisted of three conditions: control, low contrast, and monocular. In the control and monocular conditions display of stimuli was kept the same. In the low contrast condition, the contrast of stimuli was reduced, this can be seen in the top left panel of the figure. Participants completed a total of 300 trials – 100 per condition.

Analytic approach

All metrics were analysed using a combination of linear and generalised linear mixed models with custom contrasts to compare variance between the three levels of Condition (Control, Monocular, Low Contrast). Generalised linear mixed models were used to analyse binomial data such as response accuracy and linear were used for continuous measures such as response time. Models were run, and their outputs examined, using the *lme4* package in R (Bates et al., 2015). We used this approach to examine several different measures. Initial models were run using treatment contrasts before being further examined using custom pairwise comparison contrasts. Estimates and their associated statistics for initial models using treatment contrasts can be found within Table 1, and the associated pairwise comparisons are detailed within the text. When using mixed models, there is not a clear-cut method for calculating degrees of freedom. As such, this ambiguity can make calculations of standard *p*-values statistically unreliable or misleading. Instead, a common approach to determine significance is to interpret associated *t* and *z* values (Luke, 2017). With that in mind, we have determined an effect to be statistically significant if its *t* or *z* value exceeds ±1.96. Each measure and their findings will now be explained in turn.

Visual search performance

Behavioural outcomes of visual search performance were similar across conditions, as can be seen in Figure 2. Response accuracy was essentially at ceiling (*Mean* = 0.98, *SE* < 0.01) and did not significantly differ across conditions (*Estimates* < = *0.01*, all *z's* < = 1.44).

Further, as shown in Figure 2, participants correctly detected the target, on average, after 3.57 s (*SE* = 120.57). However, these correct-response reaction times significantly differed across two of the three conditions. First, we observed a significant difference between the control and monocular condition (*Estimate* = −161.90, *SE* = 62.40, *t* = −2.59). Thus, participants were ∼162 ms quicker to correctly identify targets within the control condition compared to the monocular condition. Second, we observed a significant difference between the control and low contrast condition (*Estimate* = −129.40, *SE* = 62.50, *t* = −2.07). Again, within control trials, participants were ∼129 ms quicker to correctly identify the target compared to the low contrast condition. We found no difference in reaction times between the low contrast and monocular conditions (*Estimate* = −32.50, *SE* = 62.40, *t* = −0.52). We next examined how participants adapted to these conditions of altered visual input from an eye movement standpoint.

Table 1. Summary of linear mixed effects model results for all measures.

Behavioural Measures	Accuracy		RT	
Predictors	*Estimate*	*Z*	*Estimate*	*t*
Intercept	66.87(0.22)	19.18	3486.49(121.07)	28.80
Low Contrast	0.95(0.23)	−0.23	129.38(62.45)	**2.07**
Monocular	0.73(0.22)	−1.43	161.92(62.44)	**2.59**

Eye Movement Measures	Single Fixation Duration		Time to Fixate Target		Verification Time		Lag-2 Distractors		Lag-2 Targets	
Predictors	*Estimate*	*t*	*Estimate*	*t*	*Estimate*	*t*	*Estimate*	*t*	*Estimate*	*t*
Intercept	201.42(5.80)	34.70	2490.49(77.58)	32.10	983.62(79.41)	12.39	0.01(0.00)	8.97	0.26(0.02)	11.76
Low Contrast	11.77(2.01)	**5.86**	177.27(54.29)	**3.70**	−51.56(57.32)	−0.90	0.00(0.00)	1.37	−0.02(0.01)	−1.77
Monocular	8.20(2.76)	**2.97**	119.45(54.40)	**2.20**	44.74(70.98)	0.63	0.00(0.00)	1.41	0.00(0.01)	0.35

Eye movement measures

As can be seen within Figure 3, we focused on eye movement measures with regard to each object type. Here, we examined fixation durations on distractors, the time to fixate targets, verification times, and finally lag-2 revisit rates.

Single fixation durations on distractors

The first eye movement measure that we examined was single fixation durations on distractor objects (see Figure 3). These were computed from correct-response trials only and were drawn from distractor objects that were fixated once and did not coincide with trial events such as responses or display changes.

We observed several significant differences between conditions. First, single fixation durations to distractors were reduced by ~ 12 ms in the control condition compared to the low contrast condition (*Estimate* = −11.77, *SE* = 2.01, *t* = −5.86). We further found a similar significant difference between the control condition and monocular condition (*Estimate* = −8.20, *SE* = 2.76, *t* = −2.97). Here, participants' single fixation durations for distractors reduced by ~9 ms in the control condition compared to the monocular condition. We found no difference, however, between the low contrast condition and the monocular condition (*Estimate* = 3.57, *SE* = 2.45, *t* = 1.45). Overall, as expected, fixation durations increased given the increasing difficulty when searching through the displays that used simulated visual impairments.

Time to fixate targets

With evidence of increases in fixation durations under conditions of simulated visual impairments, it seems

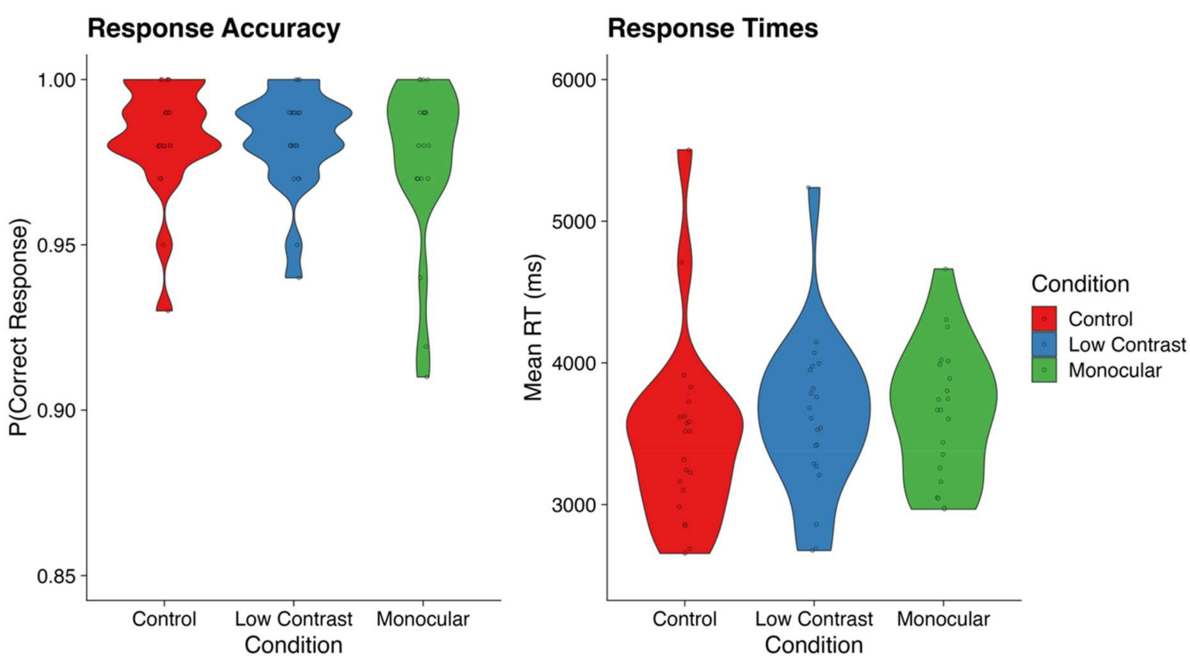

Figure 2. The effects of simulated visual impairments on response accuracy and response times.
Note: Errors bars represent ± standard error.

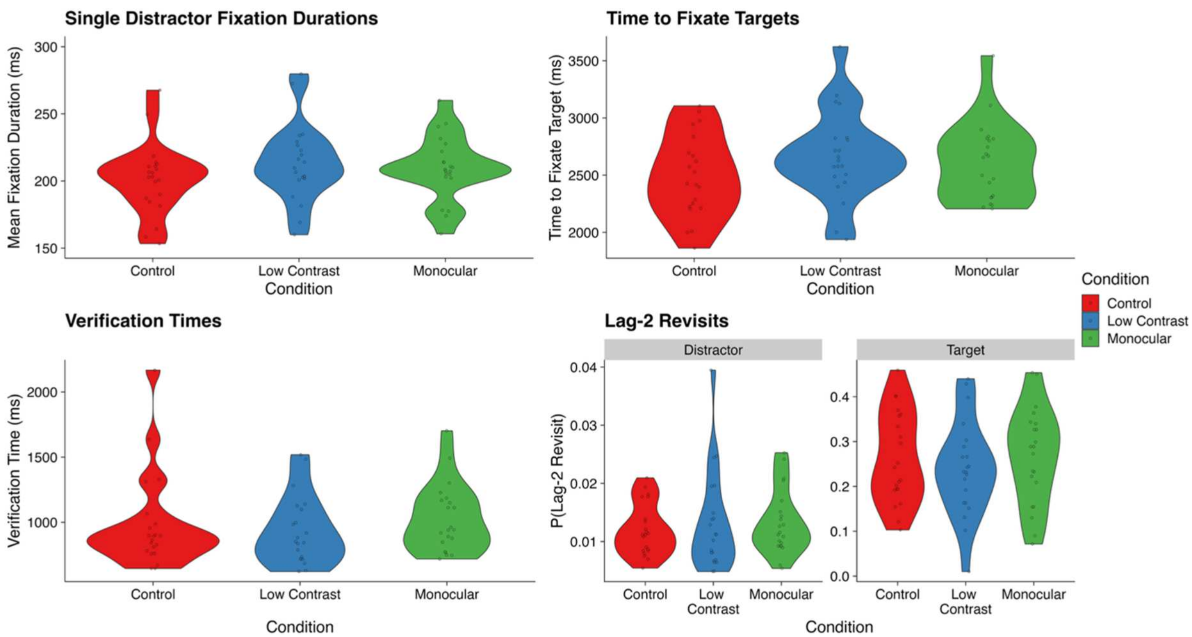

Figure 3. The effects of simulated visual impairments on single distractor fixation durations, time to fixate targets, verification times, and Lag-2 Revisits.

Note: Errors bars represent ± standard error.

likely that the time to fixate targets should also increase for these conditions. Time to fixate targets was calculated as the time between display onset and the first fixation that fell within the specific distance to the target object. And indeed, our analyses confirmed this, as can be seen in Figure 3. Here, participants were quicker at fixating the target by ~179.22 ms in the control condition compared to the low contrast condition (*Estimate* = −177.30, *SE* = 54.30, *t* = −3.27). Likewise, participants were also quicker to identify the target by ~121.74 ms in the control condition compared to the monocular condition (*Estimate* = −119.40, *SE* = 54.40, *t* = −2.20). However, we found no evidence of differences between the low contrast and the monocular conditions (*Estimate* = 57.80, *SE* = 54.40, *t* = 1.06).

Verification times

Next, we examined verification times, calculated as the time between first fixating the target and responding, which we used to determine any effects of the simulated visual impairments upon participants' ability to identify target objects (see Figure 3). Overall, we observed no significant difference within verification time between conditions (*all estimates* <= 96.30, all *t's* <= 1.90).

Lag-2 revisit rates

Finally, we examined lag-2 revisit rates for distractors and targets, to test whether higher-level mechanisms may also play a role (see Figure 3). For distractor objects, we found no evidence of experimental condition influencing lag-2 revisit rates (*all estimates* <= 0.00, *all t's* <= 1.41). However, when examining target objects, we observed a small difference in lag-2 revisit rates of ~0.03 within the monocular condition compared to the low contrast condition (*Estimate* = −0.03, *SE* = 0.01, *t* = −2.12). We found no evidence of a difference between the remaining conditions (*all estimates* <= 0.02, *all t's* <= 1.77).

Overall, then we found no clear evidence that lag-2 revisit rates increased when the simulated visual impairments were used, which was contrary to our expectations.

Null results

To better confirm our null findings, we conducted some additional Bayesian analyses on verification times and lag-2 revisit rates, both of which provided null results across the board. Modelled effects are presented in Table 2 and were calculated within R (R Core Team, 2023) via the *brms* package (Bürkner, 2017) and Bayes factors were computed via the *bayestestR* package (Makowski et al., 2019). Bayes factors are the result of a likelihood ratio test between an alternative hypothesis and a null hypothesis. Bayes factors greater than 1.00 indicate stronger evidence towards the alternative hypothesis, whilst Bayes factors of less than 1.00 suggest stronger evidence towards the null hypothesis. For an effect to be deemed trustworthy, it required

Table 2. Bayesian analyses – Verification time & lag-2 revisit rates.

	Verification Times			Distractor Lag-2 Revisits			Target Lag-2 Revisits		
Predictors	Estimate	CIs	BF_{10}	Estimate	CIs	BF_{10}	Estimate	CIs	BF_{10}
Intercept	963.03 (58.60)	845.68- 1076.20	1.35×10^{15}	−0.00 (0.00)	−0.00-0.00	0.002	0.02 (0.26)	−0.00-0.05	0.07
Low Contrast	−0.03 (1.01)	−2.01-1.97	1.01	−0.00 (0.00)	−0.00-0.00	0.002	−0.00 (0.02)	−0.03-0.05	0.01
Monocular	0.03 (1.00)	−1.91-1.99	0.97	−0.00 (0.00)	−0.00-0.00	< 0.001	−0.03 (0.01)	**−0.05–0.00**	0.13

Note. CIs = Credible Intervals; BF = Bayes Factor; Bolded CI values = CIs that did not pass through zero; Bolded BF values = BF > 3.20. Values in parentheses represent the associated standard error values. All R-Hat values = 1.00. Effects were deemed reliable if CIs did not pass through zero and BF > 3.00.

both a 95% credible interval (CI) that did not pass through zero, and a Bayes factor of greater than 3.00.

These additional analyses further confirmed what was observed within our prior analyses. We found no evidence that our manipulation had any influence over verification times (all CI's included zero, and all BF_{10}'s <= 1.01). Next, within our analyses of distractor lag-2 revisits, we observed extremely strong evidence in favour of the null hypothesis (all CI's included zero, and all BF_{10}'s <= 0.002). Finally, within our analysis of target lag-2 revisit rates, we again observed evidence in favour of the null (all BF_{10}'s <= 0.13). Whilst we observed a very small significant effect for the monocular condition within our prior frequentist analysis, within this Bayesian approach, whilst the CI did not pass through zero, the associated Bayes factor was substantially below 1.00. As such, this suggests that the observed result was small and unreliable.

To summarise, our Bayesian analyses confidently confirm that our manipulation had no influence upon either verification time or lag-2 revisits.

Discussion

In the present study, we examined how eye movement behaviour is modulated when the visual input is degraded. From a theoretical perspective, our findings speak to a fundamental and highly important aspect of eye movement control: how, when and why are fixations terminated, and subsequent saccades initiated? The oculomotor system faces what we have referred to as a "Goldilocks problem" when deciding to terminate fixations. If fixations are terminated too early, objects may be misidentified, and/or revisits to those objects may be required. If fixations are terminated too late, time will be wasted fixating those objects for no gain to the searcher. Instead, a balancing act is required to terminate fixations at a time that is "just right". Past work has shown that the point at which fixations are terminated is based upon a top-down prediction, that is known to be influenced by the expected difficulty of stimulus identification but not by the likelihood that the object being fixated will be the target (Godwin et al., 2017), with the oculomotor system exhibiting a preference for not increasing fixation durations and instead accepting the penalty of increased lag-2 revisits. Here, we studied the former of these two factors that influence fixation termination by increasing the difficulty of stimulus identification using simulated visual impairments. We examined eye movement behaviour during a simple search task, following previous work (Godwin et al., 2017). Participants were engaged in a control condition, a monocular condition where participants viewed the display with their non-dominant eye only, and a low-contrast condition where the stimuli were presented at a reduced level of luminance contrast.

As would be expected from a simple task of this nature, we found no evidence of differences in response accuracy between the different conditions, though RTs were slowed when the simulated visual impairments were used, relative to the control condition. This general slowing was also reflected in the eye movement record. Compared to the control condition, single fixation durations on distractors and the time taken to fixate the target were increased when the simulated visual impairments were used. These results were in line with our predictions and past research: put simply, fixation termination is delayed in order to facilitate more detailed processing of visual information when the visual input is impaired or degraded. Contrary to our predictions, however, we found no evidence of shifts in behaviour relative to the control for either verification times or lag-2 revisits, and we followed this up with a confirmation using Bayesian analyses.

How might we reconcile our findings with previous research? A simple story emerges from our results aligned against the findings of Godwin et al. (2017), who found that the oculomotor system was quite conservative when adapting the termination of fixations to the nature of the task at hand: rather than terminate fixations at a later time point, instead an increase in lag-2 revisits when the probability of any given object being the target decreased. Our results suggest that, when bottom-up input is degraded or impaired, then the oculomotor system does indeed adapt fixation durations to a sufficient degree so as to preclude the need to make additional lag-2 revisits. We can therefore conclude that there is a divergence in how the oculomotor system responds to different demands placed on it, in terms of impoverished bottom-up input (increase fixation durations, and no increase in lag-2 revisits) and in terms of shifting likelihoods of targets being fixated (no change in fixation durations, increase in lag-2 revisits). Future studies along these lines could consider combining our simulated visual impairments used here alongside shifts in the likelihood that a fixated object will be the target. When these two combine, as they may often do in everyday searches, do fixation durations increase alongside lag-2 revisit rates?

Implications for visual impairments and future research

Simulating visual impairments is an important method to understand how our visual system adapts to sudden or gradual changes in visual input (Maiello et al., 2018). In our study, we found that, in the short term, the visual system adapts to visual search under monocular vision and low-contrast conditions by engaging low-level mechanisms that adjust fixation durations. This adaptation suggests that the visual system can quickly compensate for degraded input by modulating the time spent processing visual information at each fixation. Future research could also investigate how these adaptations occur over longer periods and whether similar mechanisms are employed in clinical populations with visual impairments such as myopia (Maiello et al., 2018), age-related macular degeneration (Rosa et al., 2021), glaucoma (Cirafici et al., 2021), and many more (Bourne et al., 2013), which exhibit more complex patterns of visual loss that may be unequal across the visual field and between the two eyes. Additional simulation work, as well as studies involving clinical populations, are needed to further understand these mechanisms. Such research could lead to the development of targeted training and rehabilitation therapies aimed at improving visual search efficiency in individuals with visual impairments.

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CRediT taxonomy roles

Under the CRediT taxonomy, the following contributions were made by the authors, with their names ordered as in the same order as the manuscript. All authors were involved in Conceptualization. HD was involved in Data Curation. UoSPC, GM, LH, ED and HG conducted Formal Analyses. Investigation was carried out by UoSPC, AP, LH, ED, and HG. Project Administration and Resources were overseen by HG. Software was developed and supported by GM and HJG. Supervision was undertaken by GM, AP, JM, HG. Validation was carried out by GM, HD, HG. Visualization was carried out by UoSPC, GM, LH, ED, HG. Writing – Original Draft and Preparation was conducted by UoSPC, LH and ED. Writing – Review & Editing was carried out by UoSPC, GM, AP, JM, HD and HG.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethical approval

Ethical approval for the study was gained from the Psychology Ethics Committee at the University of Southampton (Study ID: ERGO 90134, Date of Approval: 01/11/24). Participants gave their written consent to be involved in the study.

Data availability statement

The analytic code and data for the study are available to access online via this web address: https://osf.io/td7jq/?view_only=8a3bd74efb6448f8b3496495f12dbd7e.

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