Assessing the Size of the Functional Field of View in a Gaze-Contingent Search Paradigm

SOFIA KRASOVSKAYA, University of Iceland, Iceland
ÁRNI KRISTJÁNSSON, University of Iceland, Iceland
JOSEPH MACINNES, Swansea University, United Kingdom

The functional field of view (FFV) is the part of the visual field centred around the current gaze position that the visual system can process in detail. Its size depends partly on physiological limitations, but its adaptability is largely determined by cognitive factors. For example, changes in the FFV often reflect the demands of a given task: it shrinks with high task demands and expands with easier tasks. Here, we placed an upright or inverted target among distractors. We manipulated the visibility of the search array during gaze-contingent search with small (6°), medium (12°) and large (18°) apertures. Aperture size affected performance, improving it when it increased from 6° to 12°, but not from 12° to 18°, suggesting an upper bound of the 'natural' aperture for this specific task. Furthermore, our results suggest that the FFV does not change in size in response to stimulus inversion.

CCS Concepts: • Human-centered computing → Human computer interaction (HCI) → HCI design and evaluation methods→ **Laboratory experiments** • Human-centered computing → Human computer interaction (HCI) → **Empirical studies in HCI**

Additional Key Words and Phrases: Functional field of view, Visual search, Visual attention, Gaze-contingent setup

ACM Reference format:
Sofia Krasovskaya, Árni Kristjánsson, and Joseph MacInnes. 2024. Assessing the Size of the Functional Field of View in a Gaze-Contingent Search Paradigm. *Proc. ACM Hum.-Comput. Interact.*, 8, ETRA, Article 223 (May 2024), 17 pages, https://doi.org/10.1145/3655597

1 INTRODUCTION

While human visual processing is highly adaptable [28,45], it is constrained by both physiological and cognitive factors. One example of this is the clear difference between the physical size of our visual field and the size of the area that we can process in detail. The term functional field of view (FFV) has been used to describe the restrictions imposed by limits in visual information processing capacity around the current gaze position. A substantial amount of research on this topic is available where varying terminology has been used, such as attentional window [6], functional

2573-0142/2024/5 - 223
https://doi.org/10.1145/3655597

viewing field, FVF [45], useful field of view, UFOV [4], area of visual conspicuity [12] and visual span [22,35]. While the FFV is sometimes compared with related concepts such as the spotlight of attention [41] or the attentional zoom lens [14] the two are nevertheless not the same. As Young & Hulleman [54] highlight, while concepts such as the spotlight and zoom lens describe attentional mechanisms that may operate separately from eye movements, the FFV is centred on the locus of fixation.

1.1 Physiological factors

Information processing in the visual field is limited by physiological constraints, for example, the difference in receptor density between the fovea and the peripheral retina [47]. The area with the highest resolution is the fovea, whose size is about as large as the projected retinal size of a thumbnail on an extended hand (~1° visual angle). The region extending beyond this point has lower receptor density and visual resolution therefore deteriorates as a function of eccentricity from the fovea.

Since the distribution of rods and cones across the retina is not uniform, visual processing of the environment is similarly not uniform across the visual field [2,9,11,23,36,39]. The foveal retina contains mainly cones while the peripheral retina is more densely packed with rods than cones [10,18,28,50]. The receptive fields of retinal ganglion cells are then responsive to particular locations within the visual field and this retinotopic organisation is maintained roughly throughout the stream of visual information processing [31,37,49].

1.2 Cognitive factors

The functional field of view (FFV) is, however, mainly constrained by cognitive, or functional factors such as visual attention. These factors can be assessed by posing such questions as how much information can we effectively handle at a given time? Does it depend on scene properties? Does it depend on the amount of information in the visual field? Does this change by task demands and cognitive load?

A common approach to studying the functional field of view is through the manipulation of stimuli or tasks that might influence task difficulty. Williams [51] used a dual-task paradigm, combining a foveal character-discrimination task and a peripheral line-orientation discrimination task. While the visual display factors were constant in the foveal character discrimination task, the cognitive load was varied between subjects by using either a physical or a category match [40]. Williams used a tachistoscope that allowed a visual field of 11° in diameter and displayed stimuli at three different eccentricities (1.66°, 3.33° and 5° from central fixation), finding that under high levels of foveal (cognitive) load participants performed worse in the peripheral line orientation discrimination task. He assessed the size of the functional field of view based on correct responses on the line orientation task, plotting iso-sensitivity contours, concluding that in the high foveal load condition the FFV was only about 2° in diameter, whereas low foveal load resulted in a functional field size of about 4° around fixation.

Motter & Simoni [34] measured changes in FFV size based on the presence or absence of overt eye movements in visual search. Their participants performed a conjunction search (for a red T among green L's) in three conditions: eye movements were either required, allowed, or suppressed. The search arrays contained either 6, 12, 24 or 48 items, and the FFV boundary was calculated based on the farthest distance of the detectable target from the fixation point. They found that when eye movements were suppressed, the size of the FFV increased over time, presumably to enable observers to gather as much information about the search set as possible, compensating for the inability to overtly attend to salient locations. They concluded that despite our ability to attend to stimuli in the periphery, we prefer to perform search, keeping the target of attention in our fovea by making eye movements, which is, in the end, a natural way of gathering information.

Further evidence showing that FFV size varies by search difficulty comes from Young and Hulleman [54]. They measured eye movement patterns in static and moving displays with varying stimulus complexity that affected the mental load associated with the search. In what they called the easy search condition, participants were asked to search for a horizontal line among other lines and line combinations while the medium and difficult search conditions involved search for a T-shaped target (medium) and a square with a smaller square in its top left corner among similar squares (difficult). Using the measured gaze coordinates and the locations of the search items, using different radii, they counted the number of fixations and the total number of items that fit within a specific aperture radius per trial, starting with a 1° aperture. Each item was counted only once so there was no overlap. The final FFV was estimated as the radius that fit 50% of the total number of search items displayed during the trial. Using this method, they estimated the size of the FFV for each condition to be 8.7°-9.7° (easy), 5.8°-6.8° (medium) and 1.7°-2.2° (difficult). To provide further support for these calculations of FFV size, Young and Hulleman performed a second experiment with the same design, but this time using an actual gaze-contingent window with three sizes: 9.7°, 4.9° and 2.4°. This approach yielded empirical support for the estimates of the FFV sizes calculated in experiment 1. Moreover, Young & Hulleman observed that on trials where item motion would not typically impede visual search, no "robustness against item motion" (as they called it), was present with the small aperture in the hard search condition. They concluded that this detrimental effect of motion was primarily due to the limited number of items available for processing within one fixation and was not directly due to task difficulty.

These findings led to an influential proposal where Hulleman & Olivers [19] challenged the prevalent assumption that visual search is item-based. They argued instead that the focus in understanding visual search (and attention more generally) should be on the functional viewing field, the topic of our current study. Hulleman and Olivers [19] argued that visual search performance is primarily determined by visual fixations rather than item numbers. According to their proposal, the size of the FFV and the number of items within it depends on several factors, such as the complexity of the visual scene, the difficulty of the search task and target characteristics. They claimed that the FFV is dynamic and depends on how discriminable the target is from the surroundings: low target discriminability results in a higher load and a smaller FFV, and vice versa for high discriminability (but see [20]; Open Peer Commentary, for criticisms of this proposal).

Krasovskaya and colleagues [24] attempted to measure whether visual performance was affected by task manipulations in a display where participants had to determine whether a target was present among a set of distractors in a 45 item grid. They manipulated the size of the stimuli to affect the difficulty of the search: on "easy" trials they used large items (1.3°) while on "difficult" trials they used smaller items (0.7°). The number of items in the display was kept constant. Participants had to manually respond if a target shown at the start of the trial was present in the search set. They found an effect of stimulus size and target presence on task performance with longer search times and lower accuracy for the small item search than the large item search. Additionally, response times were longer and accuracy lower on target-absent trials than target-present trials. While this study showed that manipulations of item size and target presence affected search difficulty, it did not reveal how much information was processed during the visual search.

1.3 The current aims

Our aim was to manipulate the functional viewing field directly to determine the amount of visual information that can pass through the FFV under different conditions. We used a gaze-centred aperture of three different sizes to directly limit the amount of visible information to test whether there was any noticeable deterioration in task performance as the aperture decreased in size. Specifically, our aim was to identify the point at which the aperture no longer had a detrimental effect on performance during a challenging visual search task. We conducted a gaze-contingent visual search experiment using artificial traffic signs that varied by colour, shape, and the identity of the object depicted on the sign. On each trial observers were presented with a target to look for and they had to find a traffic sign having that particular symbol, colour, and orientation (task and stimuli adapted from [7]).

We also tested whether stimulus manipulations might affect the cognitive load associated with the search task, assessing their interaction with the size of the FFV. To this end, here we used a similar design to Krasovskaya et al. [24] but added a gaze contingent aperture (centred on the fixation point). We also contrasted two different ways of presenting the stimuli, either upright or inverted, to test the effects of target identifiability during search. Before the search began, participants briefly saw the target they had to search for. The target was always shown in an upright position during this 'preview' period, on trials where the stimuli were upright the level of target abstraction would be low, while trials containing inverted stimulus sets (including the target) would have a higher degree of abstraction associated with the mental rotation of the target image. We expected that if the FFV truly differed in the two orientation conditions (Upright vs. Inverted, which we assumed would affect identification of the targets), then search performance in each condition would start deteriorating at different aperture boundaries.

2 METHODS

2.1 Data recording

The stimuli were presented on a 24-in. BenQ XL2411Z screen with a resolution of 1,920 × 1,080 pixels and a refresh rate of 144 Hz. Eye movement recordings were carried out monocularly on the dominant eye at a frequency of 1000 Hz using an EyeLink 1000 Plus eyetracker (SR Research Ltd, Osgoode, Ontario, Canada). Eye dominance was determined using the Porta test. Participants were seated in a height-adjustable chair with their head position fixed by a chinrest in a slightly darkened room. The distance to the screen was 90 cm. PsychoPy Coder [38] was used for stimulus presentation and manual response collection.

Experiment design. Twenty participants (12 female, mean age = 31) were instructed to search for a target traffic-sign among distractors and perform a two-alternative-forced-choice (2AFC) task, judging whether the target had a dot on the left or right of the figure on the sign. At the start of each trial (the 'preview'), a target traffic sign was shown at screen centre for 500 ms (Fig. 1a). After this, 45 stimuli were presented for up to 7000 ms, which included the target and 44 distractors chosen randomly from the full set. Inside each traffic sign there was a small black dot on the left or the right side of the icon. Participants had to find the target (present on all trials) and manually respond which side the dot was on ('a' for left, 'd' for right). The trial ended as soon as a response was provided or if there was no response within the 7000 ms period. In the latter case the trial was registered as a 'no response' trial. The target was present on all trials.

We manipulated target orientation in an effort to affect the degree of abstraction associated with the search. For all conditions, the target preview before the search was presented in an upright position, but the rotation of the target in the search array differed by condition (Fig. 1b). On low abstraction trials the target and the search set stimuli were presented in an upright position, but for trials that required mental rotation, the search stimuli and target were inverted during the search (Fig. 1c). We expected that having to perform a mental rotation of the target could potentially affecting search performance. The left and right positions of the black dot for the 2AFC task did not have to be mentally inverted, i.e., left was reported as participants' left ('a' key) and right coincided with participants' right ('d' key). In addition to the orientation manipulation, we added a gaze-contingent aperture that followed participants' gaze location in an online fashion. We used three different aperture sizes: 6°, 12° and 18° (Fig. 1d).

Each participant performed a total of 600 trials separated into six blocks of 100 trials and they could rest between the blocks. Each aperture size was fixed at two blocks, and the order of the blocks was randomised for each participant. Upright and inverted trials were mixed in every block, so participants could not predict the orientation of the next trial. An example of each condition is presented in Fig. 1. Each participant performed 30 training trials with an aperture of 20° before starting the main experiment.

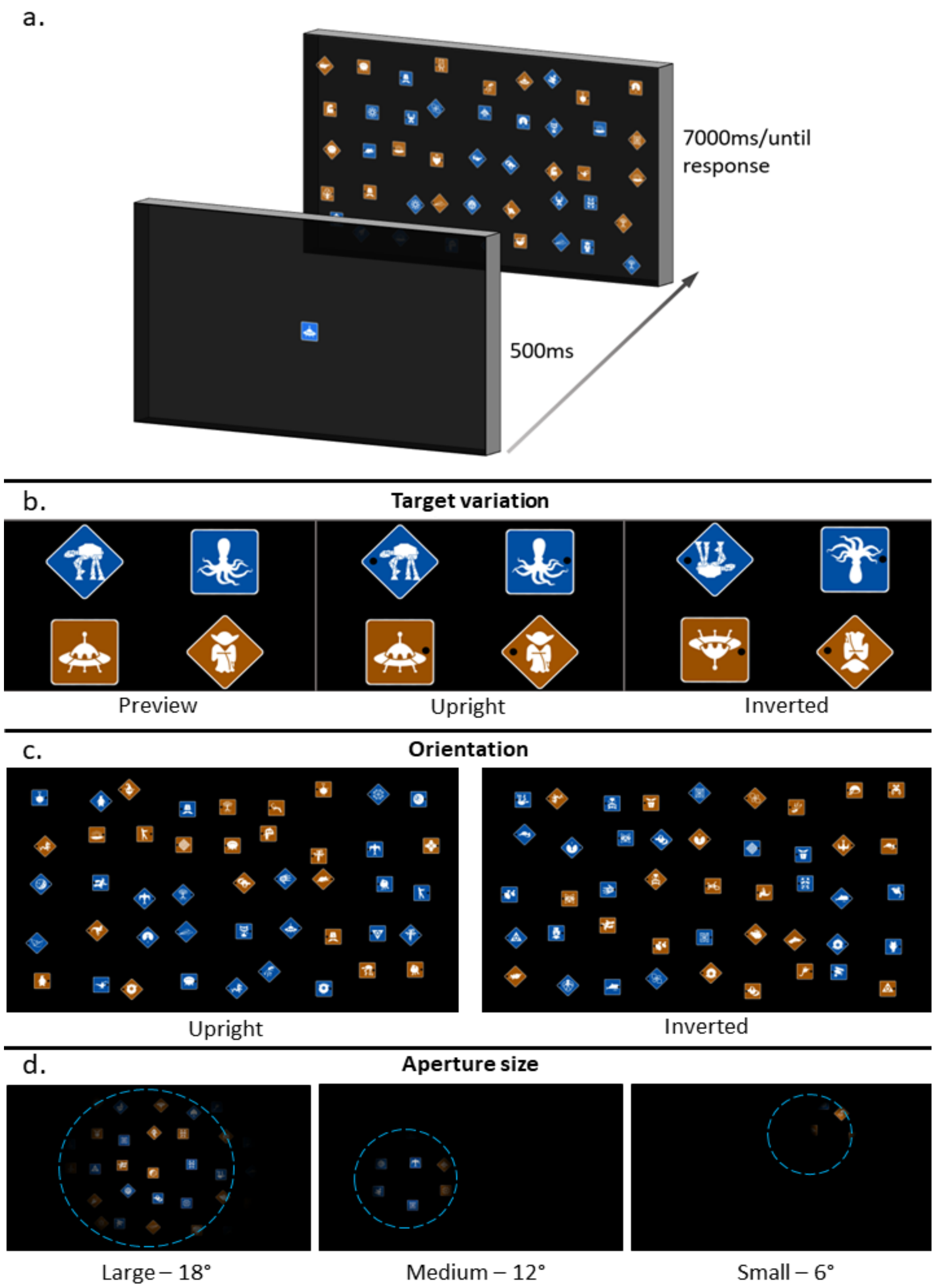

Fig. 1. General experimental design and the different conditions used in the experiment. The figure depicts the general design and possible experiment variations. The timing applies to one experimental trial. 1a: First, a target was shown for 500 ms. Then, a search set containing 45 icons appeared for 7 seconds during which a response was expected. The trial ended as soon as there was a response or when the 7000 ms time limit ended. 1b, left panel: example target variations in the preview at the start of the trial (500 ms). There were four possible target options: a blue diamond, a blue square, a brown square, a brown diamond. 1b, central panel: example target variations in the upright condition. 1b, right panel: example target variations in the inverted condition. There were 64 possible images for each shape and colour combination. The black

dots for the 2AFC task were randomly overlayed either on the left or on the right side of each icon. 1c: possible search set orientations: upright (left panel) and inverted (right panel). 1d: the three possible aperture sizes in the experiment.

2.2 Analyses

We conducted separate analyses of accuracy and response times for manual responses. Orientation and aperture size were the independent variables, where a repeated measures ANOVA was used for both analyses (with the following R packages: Stats, Effectsize and Emmeans).

We further analysed saccades and fixations to compare fixation durations and saccade amplitudes for each of the orientations and aperture size conditions using a repeated measures ANOVA, using the Effectsize and Emmeans R packages. The number of fixations is also a typical measure of potential differences in search behaviour (such as for different search conditions). However, as the analyses of the number of fixations and fixation durations essentially converge in this study, it is not included in the main analysis section (presented in Appendix A).

3 RESULTS

3.1 Accuracy

We analysed the proportion of correct, incorrect and no response trials for each aperture size (Fig. 2a). We calculated accuracy as a function of orientation and aperture size (Fig. 2b) by first counting the number of responses given for each unique combination of participant number, accuracy, orientation, and aperture size and then separately calculating the percentage of correct responses for each combination.

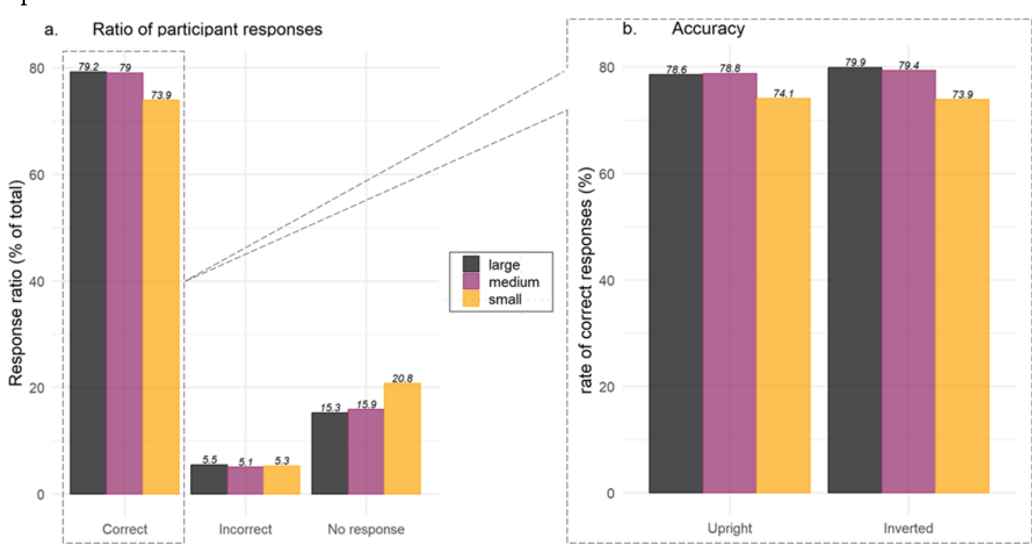

Fig. 2. Response accuracy rates for the different experimental conditions. Panel a shows the accuracy ratios of participant responses to the total number of responses given aperture size. On the x-axis from left to right: 'Correct' for correct responses, 'Incorrect' for incorrect responses, 'No response' for trials where no manual response was given within 7000 ms after the start of the search. Panel b depicts the rate of accuracy given orientation and aperture size. On the x-axis from left to right: 'Upright' for upright

trials, 'Inverted' for inverted trials. Colour coding for both panels: yellow – small aperture, purple – medium aperture, gray – large aperture.

Overall, 77.4% of participant responses were correct, and we can therefore assume that participants understood the task and were able to perform it relatively well (chance performance = 50%). The number of no response trials (17.3%) was over three times higher than the number of incorrect trials (5.3%).

To assess whether orientation and aperture size significantly affected accuracies, we performed a 2x3 repeated measures analysis of variance on the accuracy rates with orientation (Upright, Inverted) and aperture size (Large, Medium, Small) as independent variables. Trials with no response were treated as incorrect responses for this analysis. The analysis revealed a main effect of aperture size ($F(2,36) = 5.543$, $p = .008$, $\eta 2 = .24$), but neither a significant effect of orientation ($F(1,18) = .404$, $p = .533$, $\eta 2 = .02$) nor an interaction between the two factors ($F(2,36) = .598$, $p = .555$, $\eta 2 = .03$). Pairwise comparisons for aperture size revealed that the main effect of aperture size was due to a significant difference between the large and the small aperture sizes (mean difference estimate = -.052, $t(36) = -2.929$, $p = .016$) and between the medium and the small aperture sizes (mean difference estimate = -.051, $t(36) = -2.836$, $p = .019$). The difference between the large and medium aperture sizes was, on the other hand, not significant (mean difference estimate = -.001, $t(36) = -.092$, $p = .995$).

3.2 Response times

Response times are shown in figure 3, for trials with both correct (panel 3a) and incorrect (panel 3b) responses. We conducted separate response time analyses on correct and incorrect trials and excluded no response trials. We performed a 2x3 repeated measures ANOVA on response times with the factors orientation (Upright, Inverted) x aperture size (Small, Medium, Large). The analysis of correct trials showed a significant main effect of aperture size ($F(2,36) = 15.580$, $p < .001$, $\eta 2 = .464$), but not of orientation ($F(1,18) = .006$, $p = .937$, $\eta 2 < .001$) and no interaction between the two independent variables ($F(2,36) = 1.521$, $p = .232$, $\eta 2 = .078$). Pairwise comparisons showed that the main effect of aperture size was due to significant differences between the large and small (mean difference estimate = -.263, $t(36) = -5.212$, $p < .0001$) and medium and small (mean difference estimate = -.219, $t(36) = -4.336$, $p = .0003$) apertures. Similar to the accuracy results, the RT difference between the large and medium apertures was not significant (mean difference estimate = -.044, $t(36) = -.876$, $p > .5$). Adjustments for multiple comparisons were made using the Tukey method. Fig. 3 shows the RT's for the different conditions.

For incorrect trials there was no significant effect of aperture size: ($F(2,34) = .142$, $p =.868$, $\eta 2 = .008$), nor any interaction between aperture size and orientation ($F(2,34) = .387$, $p = .682$, $\eta 2 = .022$). However, there was an effect of orientation, with faster RT's on inverted than upright trials for incorrect responses (mean difference estimate = -.286, $t(17) = -2.124$, $F(1,17) = 4.510$, $p = .048$, $\eta 2 = .209$) (Fig. 3b).

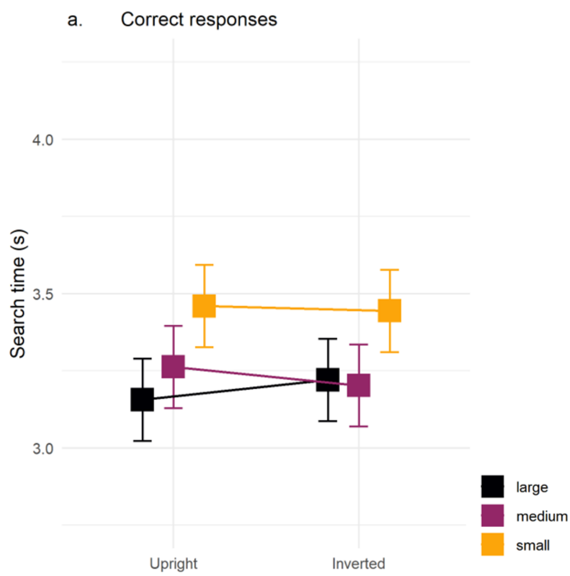

Fig. 3. Response times. The figure depicts the response times on correct (panel a) and incorrect (panel b) trials. Panel a shows the non-significant interaction of search times for correct responses in the upright ('Upright' on the x-axis) and inverted ('Inverted' on the x-axis) conditions given the large (gray), medium (purple) and small (yellow) aperture sizes. Panel b shows that response times on incorrect inverted trials were faster than on incorrect upright trials for all aperture sizes. Trials with no response were excluded from the analysis for both correct and incorrect trials. Square points represent the mean, error bars are 95% CIs.

3.3 Eye movements

3.3.1 Preprocessing. Eye movement data were preprocessed using the following parameters: for saccades we only included amplitudes between .5° and 20°, durations between 10 and 60 ms and peak velocities between 40 °/s and 750 °/s. For fixations, we only analysed durations falling between 60 ms and two standard deviations from the mean (mean = 243.214 ms, SD = 154.545 ms, fixDur min = 60 ms, fixDur max = 552 ms). Only saccades and fixations occurring during stimulus presentation were included, with a total of 150926 saccades and 167612 fixations remaining after preprocessing. To assess the quality of the saccade detection algorithm, we looked at the relationship between saccade amplitude and peak velocity (the main sequence) of the detected saccades by fitting a square root model with their peak velocity and square root of amplitude values [16,27]. For our data containing 150926 saccades after preprocessing, the coefficient of determination demonstrated a good fit ($R2 = .759$).

3.3.2 Saccade amplitude. We performed a 2 (orientation) x 3 (aperture size) x 3 (accuracy) repeated measures ANOVA with saccade amplitudes as dependent variable. We found a main effect of aperture size ($F(2,35) = 67.338$, $p < .001$, $\eta 2 = .794$) that reflected the difference between the large and small apertures (mean difference estimate = .721, $t(35) = 10.784$, $p < .0001$) and the medium and small apertures (mean difference estimate = .621, $t(35) = 9.111$, $p < .0001$). The difference between the large and medium apertures was not significant (mean difference estimate = .099, $t(35) = 1.455$, $p = .325$). The effects of orientation and accuracy were not significant ($F < 1$,

$p > .5$, $\eta 2 < .05$). Adjustments for multiple comparisons were made using the Tukey method. The mean amplitudes for each condition plotted by response accuracy are shown in Figure 4.

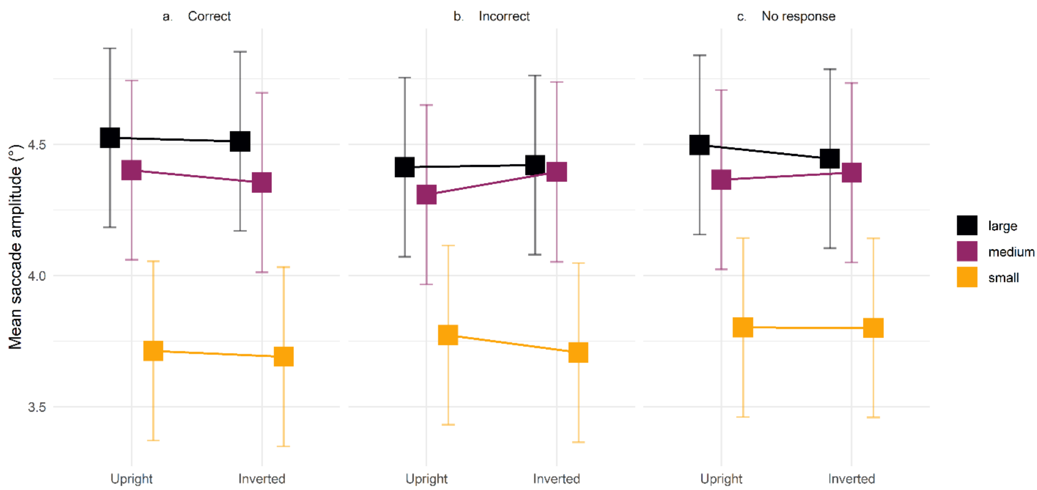

Fig. 4. Mean saccade amplitude. The figure depicts the mean amplitudes for correct (panel a), incorrect (panel b) and no response (panel c) trials on upright ('Upright' on the x-axis) and inverted ('Inverted' on the x-axis) trials given the large (gray), medium (purple) and small (yellow) aperture sizes. Square points represent the mean, and error bars are 95% CIs.

3.3.3 Fixation durations. A 2 (orientation) x 3 (aperture size) x 3 (accuracy) repeated measures ANOVA showed that aperture size affected fixation durations ($F(2,35) = 44.042$, $p < .0001$, $\eta 2 = .715$). Pairwise comparisons revealed a significant difference in fixation durations between the large and small apertures (mean difference estimate = -13.418, t(¬¬35) = -8.488, $p < .0001$) and medium and small apertures (mean difference estimate = -12.421, $t(35) = -7.698$, $p < .0001$). Notably, the difference between large and medium apertures was not significant (mean difference estimate = -.998, $t(35) = -.618$, $p > .5$). Adjustments for multiple comparisons were made using the Tukey method. A within-subjects analysis of variance showed a significant effect of accuracy ($F(2,215) = 32.325$, $p < .0001$, $\eta 2 = .231$) caused by differences between correct and no-response values (mean difference estimate = 8.500, t(¬¬215) = 6.540, $p < .0001$) and incorrect and no-response values (mean difference estimate = 9.54, t(¬¬215) = 7.312, $p < .0001$). This effect was not seen, however, when correct and incorrect responses were compared (mean difference estimate = -1.04, t(¬¬215) = -.795, $p > .5$). The effect of orientation was not significant ($F < 1$, $p > .1$, $\eta 2 < .05$). The mean durations of the fixations for each condition and accuracy are shown in Figure 5.

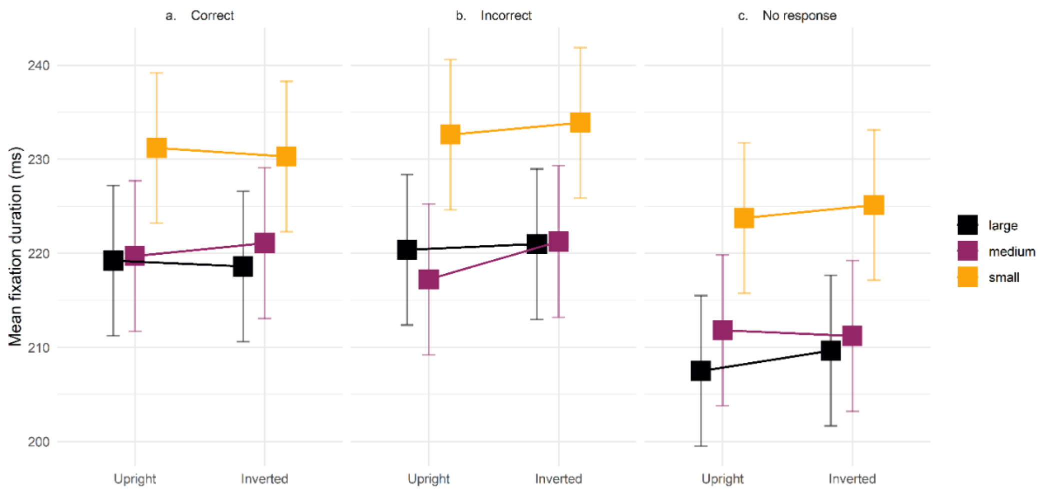

Fig. 5. Mean fixation durations. The mean duration of fixations for correct (panel a), incorrect (panel b) and no response (panel c) trials on upright ('Upright' on the x-axis) and inverted ('Inverted' on the x-axis) conditions given the large (gray), medium (purple) and small (yellow) aperture sizes. Square points represent the mean, and error bars are 95% CIs.

4 DISCUSSION

Our aim was to assess the size of the functional viewing field during a visual search task by directly manipulating the amount of available visual information at any given moment with a gaze contingent mask that covered the whole display except for an aperture at the centre of gaze. We manipulated the size of the aperture to assess the point where it no longer had a detrimental effect on performance. The most notable result is that performance measured by both search time and accuracy was by far the worst for the smallest aperture (6°), but there were no significant differences between the effects of the medium (12°) and large (18°) aperture sizes. This suggests that the medium aperture could be considered an upper boundary of the FFV for this particular task – in other words, there is little benefit to increasing the size of the FFV beyond this. Furthermore, we tested whether the orientation of the stimuli would modulate the size at which our aperture changed performance. There was no significant interaction between the upright and inverted conditions, however. In fact, if anything, the trend was for lower response times for the inverted than upright stimuli on medium aperture trials, but this was not significant.

4.1 Assessing the functional field of view

We found strong evidence that visual search performance is determined by the amount of information accessible through the FFV. Our results indicate that the medium-sized aperture (12°) was the most optimal of the three in terms of matching the natural aperture for our specific task. We reach this conclusion because there were no response time or accuracy benefits of increasing aperture size above the medium one, while accuracy was lowest and response times largest for the smallest aperture. This matches existing evidence that search is more efficient when fewer saccades into the periphery are needed to find a target of interest [19,46,52]. This also matches the size of the largest eccentricity condition (5° from central fixation) that Williams [44] used his study but diverges from his findings of a 2° FFV in the high foveal load condition and 4° in the low foveal load condition. Task differences may explain this seeming discrepancy. While participants in Williams' study [44] had to perform a discrimination task, keeping their gaze steady on a fixation point, the participants in the current study had to scan the visual scene until they found the target, or the trial ended.

We expected the optimal size of the aperture to change for the inverted and upright conditions with a smaller optimal aperture for the former, as smaller FFV has been associated with increased search difficulty [6]. This expectation was also guided by existing literature and theoretical frameworks supporting the effect of stimuli orientation in task load manipulations. For example, Yin [53] demonstrated that mono-oriented objects increased the difficulty in memory tasks when presented upside-down. Rock [44] studied how humans perceive various figures in different orientations and highlighted the challenges associated with mental rotation. Further studies by Beitner et al. [5], Evans and Treisman [15] and Epstein et al. [13] have supported this. Finally, inversion effects have been supported by neuroimaging studies [1,26]. However, the effects of orientation manipulation used in our study were not significant. There are several potential explanations for this. First, the search task might have been too difficult in both orientation conditions, creating a 'ceiling effect' where participants reached maximum performance with little room for improvement. Another potentially interesting explanation involves object polarity and symmetry. According to Leek and Johnstone [29], salient polar features (located at the end of the object's principal internal axis), provide a reliable reference point that guides the viewer's recognition of the object in any orientation axis. McMullen and Farah [33] found that only symmetrical, and not asymmetrical, stimuli lose the effect of orientation. However, this lack of sensitivity to orientation only appeared after practice – performance for misoriented object recognition was improved after participants were repeatedly exposed to the same set of stimuli (our participants were repeatedly exposed to the same set of stimuli with a training set before the main task). Moreover, most of the stimuli used in our study were symmetrical. This symmetry, combined with practice obtained throughout 600 trials could have facilitated object recognition in the inverted condition. Moreover, participants could have also created internal templates with some salient, potentially polar, features that guided their performance.

Another explanation for the lack of the inversion effect may lie in the way we manipulated the FFV. Aperture sizes in our experiment were chosen to fit approximately 4, 6-8 and 15-16 icons within one fixation for the small (6°), medium (12°) and large (18°) apertures, respectively. This was different from the aperture sizes used by Young and Hulleman [54], for example (for the small, medium and large apertures they used 2.4°, 4.9°and 9.7°, respectively, estimated from gaze coordinates; see Introduction). When we used a 2° aperture in a previous gaze-contingent study [25], our participants were unable to scan the search set and provide correct manual responses on more than 50% of the trials within the time limit. We therefore increased the aperture size to 4°, which allowed observers to respond correctly on over 50% of the trials. The different optimal aperture sizes may also reflect other task differences between the two studies. Our search display included a much larger item set than Young and Hulleman's [54] (45 items versus maximum 18 items, respectively) and our stimulus manipulations differed (shape, colour and icon combinations in static upright and inverted positions instead of static and moving monochromatic lines, T among L's and squares within squares). Another important difference is that there was no 'target absent' condition in our study – the target was present on all trials. This task difference enforced search until either a target was found, or the trial ended, without allowing for a strategic 'cutoff' [8,54] on absent trials. Knowing that the target is always present, participants may have responded more confidently on erroneous trials, as the probability of a wrong response is lower than in the target absent condition.

Finally, we enforced a 7000 ms time limit on responses and the number of no response trials (17.3%) was over three times higher than the number of incorrect trials (5.3%), and much higher than the number of no responses in Young and Hulleman (<1% at 14.6 s display duration). The largest part of these no-response data consisted of trials from the smallest aperture condition where observers were most likely to "time out" after 7 seconds.

Our stimuli were randomly pulled from the same set and on inverted trials all the stimuli were inverted. This might have set the baseline for target-distractor discriminability at a level where it did not significantly differ between upright and inverted trials, making the search within the two conditions equally difficult. According to Young and Hulleman [54] this difficulty in target-distractor discriminability should have enforced serial search on both upright and inverted trials. However, the difference in aperture size (small vs. medium) significantly affected performance, suggesting the use of parallel search in both aperture conditions. The boundaries of the small aperture could have prevented effective comparisons of potential targets when one of them was occluded by the mask (see discussion in [21]).

4.2 Eye movements

We also measured any potential differences in oculomotor behaviour by aperture size. Aperture size affected both saccade amplitudes and fixation durations with longer durations and lower amplitudes for the small than the medium and large apertures. This finding agrees with claims in the literature that larger saccades are exploratory, involving covert processing of peripheral information for decisions on the next potential fixation location [3,17,42,48]. The increase in fixation durations on small aperture trials differs from the findings of Young and Hulleman [54], who found no such differences between different aperture sizes. However, findings similar to ours have been reported before. For example, during reading and visual search, fixation durations increase with increased difficulty [22] (also see [43] for a review), as well as with the viewing distance [35]. Aperture size may have influenced abstraction levels by limiting the amount of peripheral information available for effective parallel processing. Increased fixation durations and decreased saccade amplitudes might therefore reflect decreased processing efficiency because of field-of-view limitations. There was also a general decrease in fixation durations on no-response trials compared to correct and incorrect trials. This reflects a larger number of fixations made on the no-response trials, probably signifying that more resources were necessary to perform the search and make a decision before time ran out. Decreased fixation durations and an increased number of fixations are, indeed, often seen in tasks with high levels of perceptual load [30,32].

4.3 Future directions

While previous research has extensively explored the impact of stimulus inversion on cognitive processes, including memory, neural activity, and perceptual mechanisms [1,13,15,26,44,53], the specific investigation into FFV within the framework of inversion has not been carried out so far, to the best of our knowledge. The absence of an inversion effect in the current study serves to improve the methods used to study the FFV in the context of stimuli manipulation. Future studies of FFV could introduce a control condition, with search sets that are fully congruent and fully incongruent with the target shape and colour, i.e., blocks where those two features are fixed. This could involve an easier baseline condition and eliminate the shape/colour mismatch that resulted in faster response times on incorrect inverted trials as opposed to upright trials. This could also provide a baseline that mixed blocks could be compared to, potentially increasing the difference between the upright and inverted conditions. Second, it would be interesting to see how removing any restrictions on response time would affect performance. Third, manipulating target presence vs. absence between trials could potentially change participants´ search strategy, resulting in a more perceptible effect of orientation. Fourth, the size of the FFV could be personalized using an incremental approach. This way the amount of input would be dynamically adapted to people with different performance levels and make the estimations of the FFV much more accurate. Finally, prevalidating the effect of stimuli adjustment before adding the gaze-contingent aperture would ensure that it is a proper approach for manipulating the amount of cognitive load associated with the task.

5 CONCLUSIONS

We manipulated the functional field of view with gaze-contingent apertures while orientation of the set varied (upright vs. inverted). We did not observe any detrimental effects of either the small or medium-sized apertures on search performance in the inverted versus upright conditions, while for the smallest aperture, performance was significantly affected. In the inversion condition we observed a trend towards an improvement of search performance with the medium-sized aperture and no deterioration in performance with the small aperture, while search in the inverted condition with the large aperture was worse compared than in the upright condition. This might be interesting to explore within an updated design that would include the suggestions from the Future directions section. In general, our findings suggest that there is no benefit of using an aperture larger than 12° specifically for the task used in the current study. We speculate that the medium-sized aperture is closest to the size of our natural FFV during the performance of this particular visual search task.

ACKNOWLEDGMENTS

Funding for this research was provided by the Icelandic Research Fund and the Research Fund of the University of Iceland (to AK).

REFERENCES

[1] Geoffrey Karl Aguirre, Rajiv Singh, and Mark D'Esposito. 1999. Stimulus inversion and the responses of face and object-sensitive cortical areas. NeuroReport 10, 1 (January 1999), 189.

[2] S J Anderson, K T Mullen, and R F Hess. 1991. Human peripheral spatial resolution for achromatic and chromatic stimuli: limits imposed by optical and retinal factors. J Physiol 442, (October 1991), 47–64.

[3] Sahand Babapoor-Farrokhran, R. Matthew Hutchison, Joseph S. Gati, Ravi S. Menon, and Stefan Everling. 2013. Functional connectivity patterns of medial and lateral macaque frontal eye fields reveal distinct visuomotor networks. Journal of Neurophysiology 109, 10 (May 2013), 2560–2570. https://doi.org/10.1152/jn.01000.2012

[4] Karlene K. Ball, Bettina L. Beard, Daniel L. Roenker, Richard L. Miller, and David S. Griggs. 1988. Age and visual search: expanding the useful field of view. Journal of The Optical Society of America A-optics Image Science and Vision (1988). https://doi.org/10.1364/JOSAA.5.002210

[5] Julia Beitner, Jason Helbing, Dejan Draschkow, Erwan J. David, and Melissa L.-H. Võ. 2022. Flipping the world upside down: Using eye tracking in virtual reality to study visual search in inverted scenes. Journal of Eye Movement Research 15, 3 (2022). https://doi.org/10.16910/jemr.15.3.5

[6] Artem V. Belopolsky and Jan Theeuwes. 2010. No capture outside the attentional window. Vision Research 50, 23 (November 2010), 2543–2550. https://doi.org/10.1016/j.visres.2010.08.023

[7] Andrey Chetverikov, Maria Kuvaldina, W. Joseph MacInnes, Ómar I. Jóhannesson, and Árni Kristjánsson. 2018. Implicit processing during change blindness revealed with mouse-contingent and gaze-contingent displays. Atten Percept Psychophys 80, 4 (May 2018), 844–859. https://doi.org/10.3758/s13414-017-1468-5

[8] Marvin M. Chun and Jeremy M. Wolfe. 1996. Just Say No: How Are Visual Searches Terminated When There Is No Target Present? Cognitive Psychology 30, 1 (February 1996), 39–78. https://doi.org/10.1006/cogp.1996.0002

[9] C. A. Curcio and K. A. Allen. 1990. Topography of ganglion cells in human retina. J Comp Neurol 300, 1 (October 1990), 5–25. https://doi.org/10.1002/cne.903000103

[10] C. A. Curcio, K. R. Sloan, R. E. Kalina, and A. E. Hendrickson. 1990. Human photoreceptor topography. J Comp Neurol 292, 4 (February 1990), 497–523. https://doi.org/10.1002/cne.902920402

[11] C. A. Curcio, K. R. Sloan, O. Packer, A. E. Hendrickson, and R. E. Kalina. 1987. Distribution of cones in human and monkey retina: individual variability and radial asymmetry. Science 236, 4801 (May 1987), 579–582. https://doi.org/10.1126/science.3576186

[12] F. L. Engel. 1971. Visual conspicuity, directed attention and retinal locus. Vision Research 11, 6 (June 1971), 563–575. https://doi.org/10.1016/0042-6989(71)90077-0

[13] Russell A. Epstein, J. Stephen Higgins, Whitney Parker, Geoffrey K. Aguirre, and Samantha Cooperman. 2006. Cortical correlates of face and scene inversion: A comparison. Neuropsychologia 44, 7 (January 2006), 1145–1158. https://doi.org/10.1016/j.neuropsychologia.2005.10.009

[14] Charles W. Eriksen and James D. St. James. 1986. Visual attention within and around the field of focal attention: A zoom lens model. Perception & Psychophysics 40, 4 (July 1986), 225–240. https://doi.org/10.3758/BF03211502

[15] Karla K. Evans and Anne Treisman. 2005. Perception of Objects in Natural Scenes: Is It Really Attention Free? Journal of Experimental Psychology: Human Perception and Performance 31, 6 (2005), 1476–1492. https://doi.org/10.1037/0096-1523.31.6.1476

[16] Agostino Gibaldi and Silvio P. Sabatini. 2021. The saccade main sequence revised: A fast and repeatable tool for oculomotor analysis. Behav Res 53, 1 (February 2021), 167–187. https://doi.org/10.3758/s13428-020-01388-2

[17] Marie-Hélène Grosbras. 2016. Patterns of Activity in the Human Frontal and Parietal Cortex Differentiate Large and Small Saccades. Frontiers in Integrative Neuroscience 10, (2016). Retrieved September 25, 2023 from https://www.frontiersin.org/articles/10.3389/fnint.2016.00034

[18] Ulrike Grünert and Paul Martin. 2020. Cell types and cell circuits in primate retina. Progress in Retinal and Eye Research 78, (February 2020), 100844. https://doi.org/10.1016/j.preteyeres.2020.100844

[19] Johan Hulleman and Christian N. L. Olivers. 2017. The impending demise of the item in visual search. Behav Brain Sci 40, (2017), e132. https://doi.org/10.1017/S0140525X15002794

[20] Johan Hulleman and Christian N. L. Olivers. 2017. On the brink: The demise of the item in visual search moves closer. Behavioral and Brain Sciences 40, (ed 2017), e163. https://doi.org/10.1017/S0140525X16000364

[21] Mitsuo Ikeda, Shinya Saida, and Takashi Sugiyama. 1977. Visual field size necessary for length comparison. Perception & Psychophysics 22, 2 (March 1977), 165–170. https://doi.org/10.3758/BF03198750

[22] Arthur M. Jacobs. 1986. Eye-movement control in visual search: How direct is visual span control? Perception & Psychophysics 39, 1 (January 1986), 47–58. https://doi.org/10.3758/BF03207583

[23] Ómar I. Jóhannesson, Jérôme Tagu, and Árni Kristjánsson. 2018. Asymmetries of the visual system and their influence on visual performance and oculomotor dynamics. Eur J Neurosci 48, 11 (December 2018), 3426–3445. https://doi.org/10.1111/ejn.14225

[24] Sofia Krasovskaya, Árni Kristjánsson, and Joseph MacInnes. 2021. The Effect of Task Difficulty on the Dynamics of Functional Field of View Adaptability. In PERCEPTION, 2021. SAGE PUBLICATIONS LTD 1 OLIVERS YARD, 55 CITY ROAD, LONDON EC1Y 1SP, ENGLAND, 203–203. .

[25] Sofia Krasovskaya, Árni Kristjánsson, and W. Joseph MacInnes. 2022. The adaptability of the Functional Field of View to task difficulty in a gaze-contingent search paradigm: a registered abstract. In PERCEPTION, 2022, Nijmegen, The Netherlands. SAGE PUBLICATIONS LTD 1 OLIVERS YARD, 55 CITY ROAD, LONDON EC1Y 1SP, ENGLAND, Nijmegen, The Netherlands, 43. . https://doi.org/10.1177/03010066221141167

[26] Tim Lauer, Verena Willenbockel, Laura Maffongelli, and Melissa L. -H. Võ. 2020. The influence of scene and object orientation on the scene consistency effect. Behavioural Brain Research 394, (September 2020), 112812. https://doi.org/10.1016/j.bbr.2020.112812

[27] S Lebedev, P Van Gelder, and W H Tsui. 1996. Square-root relations between main saccadic parameters. Investigative Ophthalmology & Visual Science 37, 13 (December 1996), 2750–2758.

[28] Sammy C. S. Lee, Paul R. Martin, and Ulrike Grünert. 2019. Topography of Neurons in the Rod Pathway of Human Retina. Investigative Ophthalmology & Visual Science 60, 8 (July 2019), 2848–2859. https://doi.org/10.1167/iovs.19-27217

[29] Charles E. Leek and Stephen J. Johnston. 2006. A polarity effect in misoriented object recognition: The role of polar features in the computation of orientation-invariant shape representations. Visual Cognition 13, 5 (March 2006), 573–600. https://doi.org/10.1080/13506280544000048

[30] Jung-Chun Liu, Kuei-An Li, Su-Ling Yeh, and Shao-Yi Chien. 2022. Assessing Perceptual Load and Cognitive Load by Fixation-Related Information of Eye Movements. Sensors (Basel) 22, 3 (February 2022), 1187. https://doi.org/10.3390/s22031187

[31] Björn Machner, Marie C. Lencer, Lisa Möller, Janina von der Gablentz, Wolfgang Heide, Christoph Helmchen, and Andreas Sprenger. 2020. Unbalancing the Attentional Priority Map via Gaze-Contingent Displays Induces Neglect-

Like Visual Exploration. Frontiers in Human Neuroscience 14, (2020). Retrieved June 27, 2022 from https://www.frontiersin.org/article/10.3389/fnhum.2020.00041
[32] George W. McConkie and Keith Rayner. 1975. The span of the effective stimulus during a fixation in reading. Perception & Psychophysics 17, 6 (November 1975), 578–586. https://doi.org/10.3758/BF03203972
[33] Patricia A. McMullen and Martha J. Farah. 1991. Viewer-Centered and Object-Centered Representations in the Recognition of Naturalistic Line Drawings. Psychological Science 2, 4 (1991), 275–277.
[34] Brad C. Motter and Diglio A. Simoni. 2008. Changes in the functional visual field during search with and without eye movements. Vision Research 48, 22 (October 2008), 2382–2393. https://doi.org/10.1016/j.visres.2008.07.020
[35] J. Kevin O'Regan, Ariane Lévy-Schoen, and Arthur M. Jacobs. 1983. The effect of visibility on eye-movement parameters in reading. Perception & Psychophysics 34, 5 (September 1983), 457–464. https://doi.org/10.3758/BF03203061
[36] G. Østerberg. 1935. Topography of the Layer of Rods and Cones in the Human Retina. A. Busck.
[37] Nadia Paraskevoudi and John S. Pezaris. 2021. Full gaze contingency provides better reading performance than head steering alone in a simulation of prosthetic vision. Sci Rep 11, (May 2021), 11121. https://doi.org/10.1038/s41598-021-86996-4
[38] Jonathan Peirce, Jeremy R. Gray, Sol Simpson, Michael MacAskill, Richard Höchenberger, Hiroyuki Sogo, Erik Kastman, and Jonas Kristoffer Lindeløv. 2019. PsychoPy2: Experiments in behavior made easy. Behav Res 51, 1 (February 2019), 195–203. https://doi.org/10.3758/s13428-018-01193-y
[39] V. H. Perry, R. Oehler, and A. Cowey. 1984. Retinal ganglion cells that project to the dorsal lateral geniculate nucleus in the macaque monkey. Neuroscience 12, 4 (August 1984), 1101–1123. https://doi.org/10.1016/0306-4522(84)90006-X
[40] Michael I. Posner and Ronald F. Mitchell. 1967. Chronometric analysis of classification. Psychological Review 74, (1967), 392–409. https://doi.org/10.1037/h0024913
[41] Michael I. Posner, Charles R. Snyder, and Brian J. Davidson. 1980. Attention and the detection of signals. Journal of Experimental Psychology: General 109, (1980), 160–174. https://doi.org/10.1037/0096-3445.109.2.160
[42] Ricardo Ramos Gameiro, Kai Kaspar, Sabine U. König, Sontje Nordholt, and Peter König. 2017. Exploration and Exploitation in Natural Viewing Behavior. Sci Rep 7, 1 (May 2017), 2311. https://doi.org/10.1038/s41598-017-02526-1
[43] Keith Rayner. 1998. Eye Movements in Reading and Information Processing: 20 Years of Research. Psychological Bulletin 124, 3 (1998), 372–422. https://doi.org/10.1037/0033-2909.124.3.372
[44] Irvin Rock. 1974. The Perception of Disoriented Figures. Scientific American (January 1974). Retrieved February 20, 2024 from https://www.scientificamerican.com/article/the-perception-of-disoriented-figur/
[45] A. F. Sanders. 1970. Some Aspects of the Selective Process in the Functional Visual Field. Ergonomics 13, 1 (January 1970), 101–117. https://doi.org/10.1080/00140137008931124
[46] Camilla Funch Staugaard, Anders Petersen, and Signe Vangkilde. 2016. Eccentricity effects in vision and attention. Neuropsychologia 92, (November 2016), 69–78. https://doi.org/10.1016/j.neuropsychologia.2016.06.020
[47] H. Strasburger, I. Rentschler, and M. Juttner. 2011. Peripheral vision and pattern recognition: A review. Journal of Vision 11, 5 (December 2011), 13–13. https://doi.org/10.1167/11.5.13
[48] Benjamin W. Tatler, Roland J. Baddeley, and Benjamin T. Vincent. 2006. The long and the short of it: Spatial statistics at fixation vary with saccade amplitude and task. Vision Research 46, 12 (June 2006), 1857–1862. https://doi.org/10.1016/j.visres.2005.12.005
[49] Brian A. Wandell, Serge O. Dumoulin, and Alyssa A. Brewer. 2007. Visual Field Maps in Human Cortex. Neuron 56, 2 (October 2007), 366–383. https://doi.org/10.1016/j.neuron.2007.10.012
[50] E. M. Wells-Gray, S. S. Choi, A. Bries, and N. Doble. 2016. Variation in rod and cone density from the fovea to the mid-periphery in healthy human retinas using adaptive optics scanning laser ophthalmoscopy. Eye 30, 8 (August 2016), 1135–1143. https://doi.org/10.1038/eye.2016.107
[51] Leonard J. Williams. 1982. Cognitive Load and the Functional Field of View. Hum Factors 24, 6 (December 1982), 683–692. https://doi.org/10.1177/001872088202400605
[52] Jeremy M. Wolfe, Patricia O'Neill, and Sara C. Bennett. 1998. Why are there eccentricity effects in visual search? Visual and attentional hypotheses. Perception & Psychophysics 60, 1 (January 1998), 140–156. https://doi.org/10.3758/BF03211924
[53] Robert K. Yin. 1969. Looking at upside-down faces. Journal of Experimental Psychology 81, 1 (1969), 141–145. https://doi.org/10.1037/h0027474
[54] Angela H. Young and Johan Hulleman. 2013. Eye movements reveal how task difficulty moulds visual search. Journal of Experimental Psychology: Human Perception and Performance 39, 1 (2013), 168–190. https://doi.org/10.1037/a0028679

A ANALYSIS OF THE NUMBER OF FIXATIONS

We analysed saccades and fixations to compare the number of fixations for each of the orientations and aperture size conditions using a repeated measures ANOVA, using the *Effectsize* and *Emmeans* R packages. As each trial differed in length based on participant response times, we took the mean number of fixations per trial.

A.1 Results: Number of fixations

A 2 (*orientation*) x 3 (*aperture size*) x 3 (*accuracy*) repeated measures ANOVA showed that aperture size affected the number of fixations ($F_{(2,35)}$ = 14.061, p < .0001, η^2 = .445). Pairwise comparisons revealed a significant difference in the number of fixations between the large and small apertures (*mean difference estimate* = .245, $t_{(35)}$ = 4.843, p = .0001) and medium and small apertures (*mean difference estimate* = .218, $t_{(35)}$ = 4.234, p = .0005). The difference between large and medium apertures was not significant (*mean difference estimate* = .026, $t_{(35)}$ = .512, p > .5). Adjustments for multiple comparisons were made using the Tukey method. A within-subjects analysis of variance showed a significant effect of accuracy ($F_{(2,215)}$ = 43.938, p < .0001, η^2 = .290) caused by differences between correct and no-response values (*mean difference estimate* = -.364, $t_{(215)}$ = -8.170, p < .0001) and incorrect and no-response values (*mean difference estimate* = -.360, $t_{(215)}$ = -8.063, p < .0001). This effect was not seen when correct and incorrect responses were compared (*mean difference estimate* = -.004, $t_{(215)}$ = -.079, p > .5). The effect of orientation was not significant (F < 1, p > .5, η^2 < .05). The mean number of fixations per second for each condition and accuracy are shown in Figure A1.

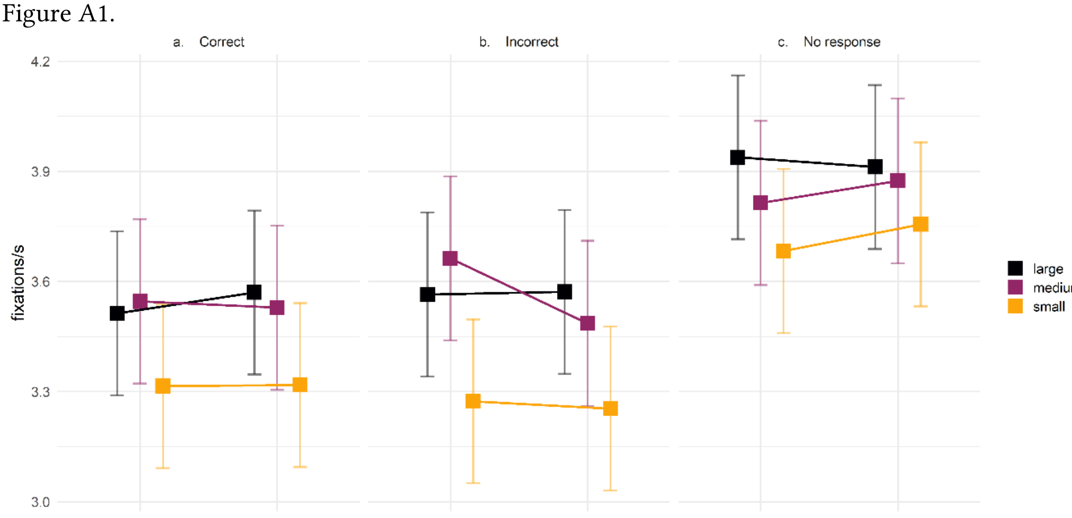

Fig. A1. Mean number of fixations per second. The mean number of fixations for correct (panel a), incorrect (panel b) and no response (panel c) trials on upright ('Upright' on the x-axis) and inverted ('Inverted' on the x-axis) conditions given the large (gray), medium (purple) and small (yellow) aperture sizes.

Received November 2023; revised January 2024; accepted March 2024.